Extendability of LPP EUV source technology in higher power (kW) / shorter wavelength (6.x nm) operation

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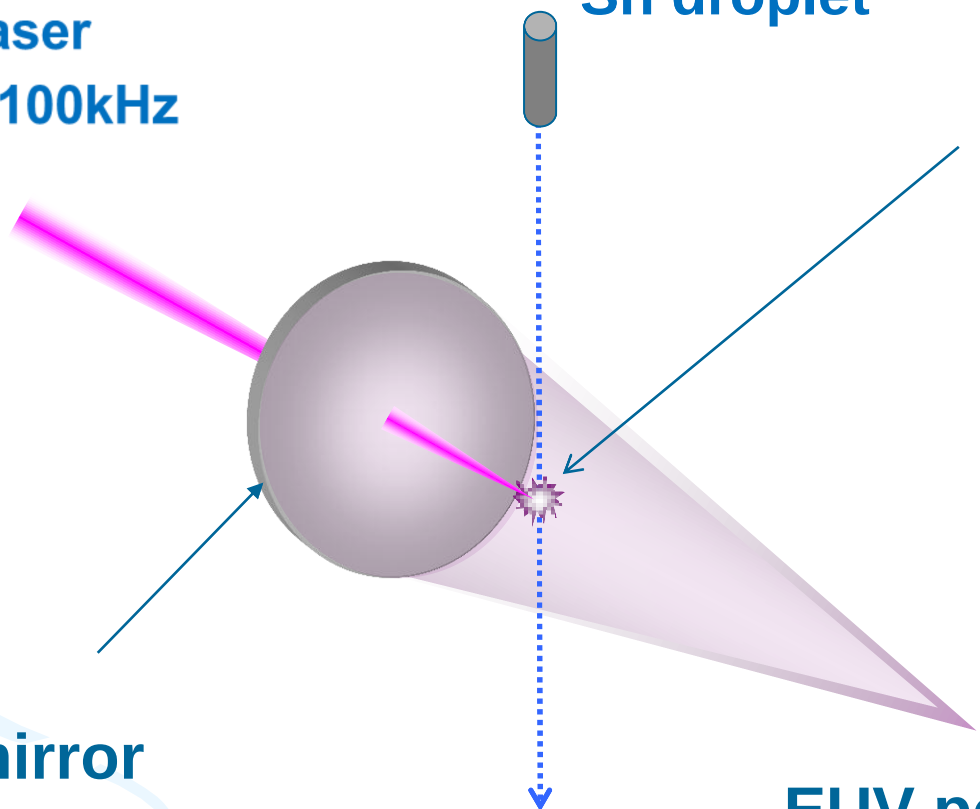
Configuration of a HVM EUV source



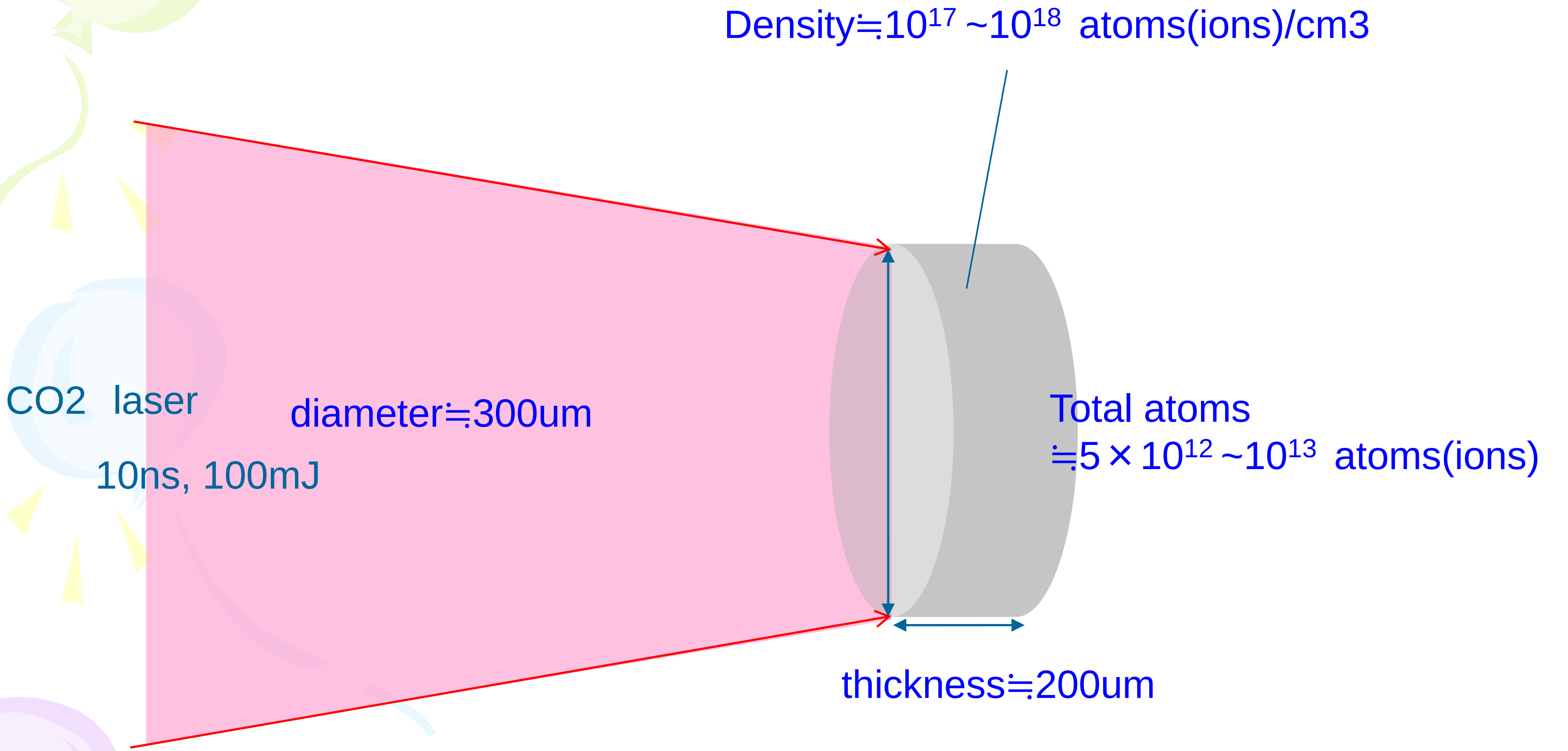
Scaling of the HVM source technology to kW range

Source main parameters	Present HVM source*	Upgrade to kW range
EUV IF power	110W (13.5nm)	1kW (13.5nm)
CO_2 laser power	20kW	50kW
Conversion efficiency	2.5%	5%**
Collection efficiency	22%	40%

*; Development of stable extreme-ultraviolet sources for use in lithography exposure systems, I.V.Fomenkov et.al. JM3 11(2), 021110 (April-Jun 2012)

**; Gigaphoton press release, July 2012

Ideal Sn target



Operational parameters present HVM source

Repetition rate	**60kHz**
Droplet diameter	30μm
Irradiation mode	Double pulse
Droplet interval	1mm
Droplet speed	60m/s
Fuel recovery	Full atomization+ magnetic ion guide (H_2 cleaning)

Operational parameters kW HVM source

Repetition rate	**150kHz**
Droplet diameter	10μm
Irradiation mode	Double pulse (picosecond prepulse)
Droplet interval	1mm
Droplet speed	150m/s
Fuel recovery	Full ionization+magnetic plasma guide (optical resonant ionization)

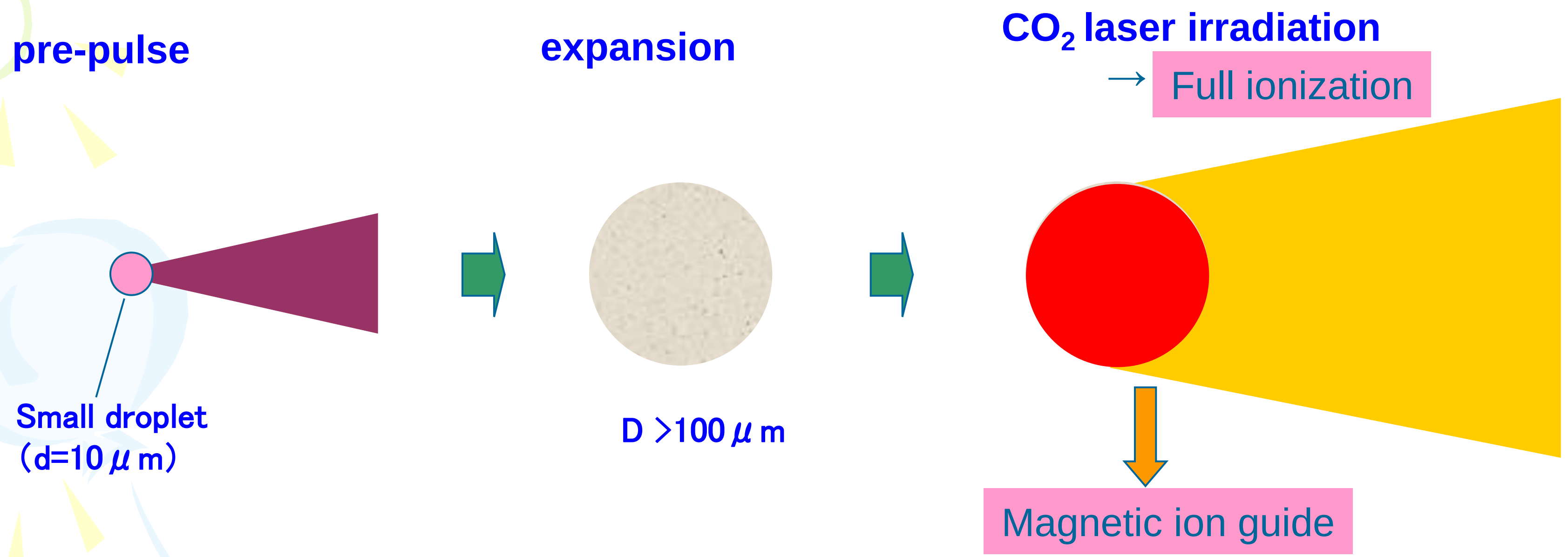
Number of included atoms

Droplet diameter (μm)	Sn	Gd
10	1.9×10^{13}	1.4×10^{13}
20	1.6×10^{14}	1.1×10^{14}
30	5.2×10^{14}	3.6×10^{14}

Atomic weight： Sn 118.7 Gd 157.25

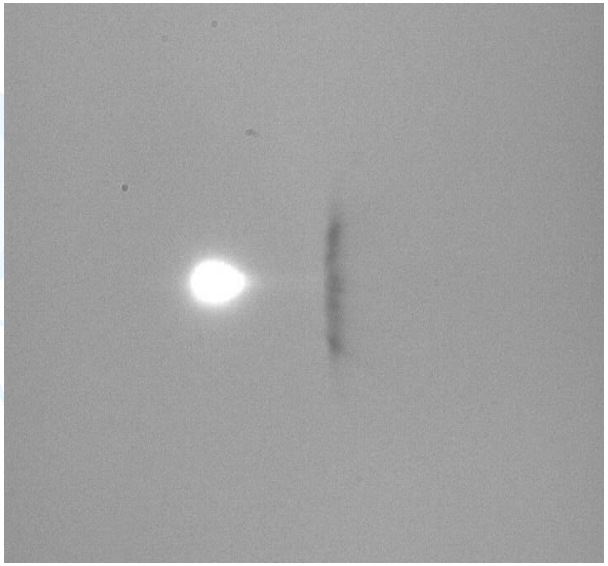
Specific gravity (g/cm^3): Sn 7.3 Gd 7.4

Optimization of pre-plasma conditioning

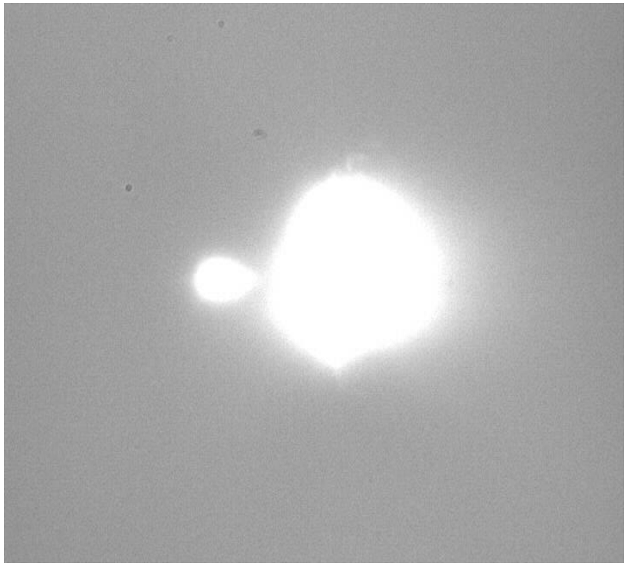


Optimize density, temperature and spatial distribution
for main pulse heating to achieve high EUV conversion efficiency
and **full exhaust of Sn atoms**

Droplet with pre-pulse irradiation



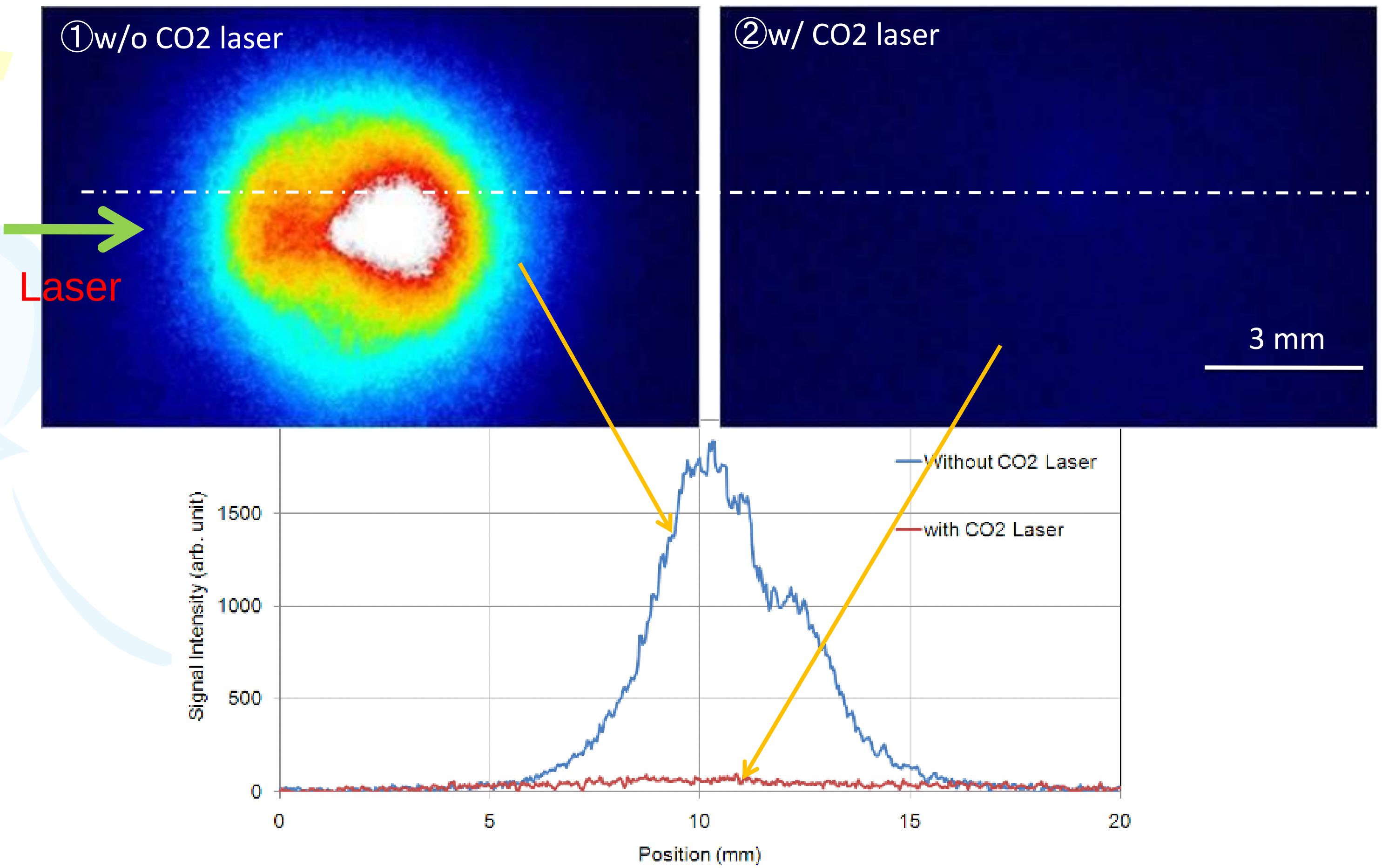
Without main pulse



With main pulse

Data by Gigaphoton Inc

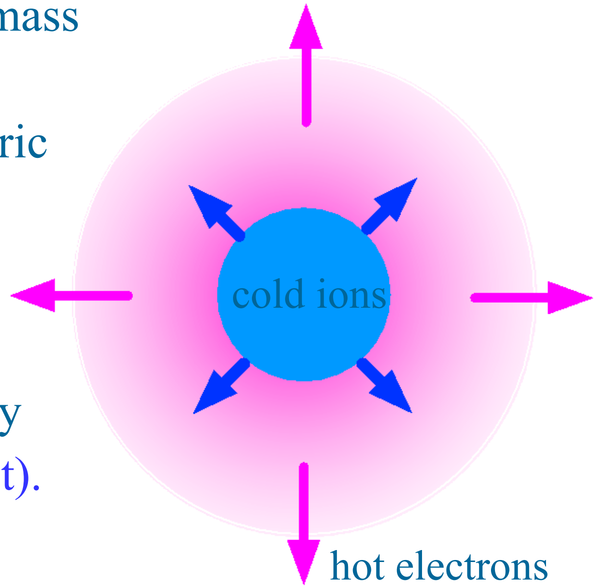
LIF measurements of neutrals in mist target



Main pulse irradiation

Plasma expansion is characterized by two phases

At $t = 0$ the electron component of a finite plasma mass is heated to a uniform temperature $T_e(r, 0) = T_{e0}$.
Hot electrons expand and create an ambipolar electric field $E(r, t)$, which drags the cold ions.



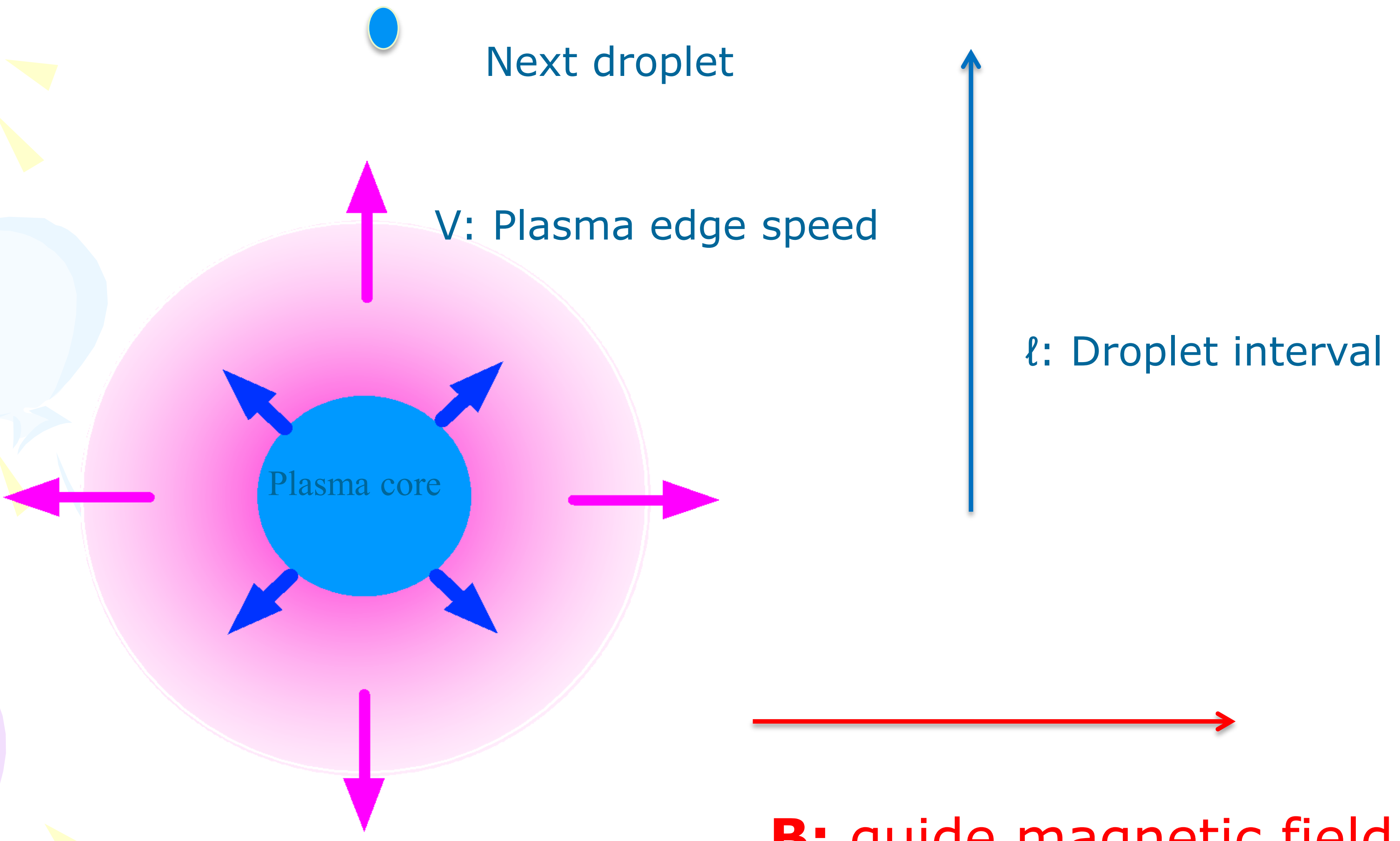
Assumptions

- There are no collisions between electrons and ions.
- At all times, the electron temperature is very quickly leveled off across the plasma volume: $T_e(r, t) = T_e(t)$.

Isothermal phase : during laser irradiation, Energy spectrum is established

Adiabatic phase : after laser irradiation, Energy spectrum is unchanged

Expansion of plasma after main pulse



Expanding plasma interference to the next droplet

ℓ (droplet interval) 1mm

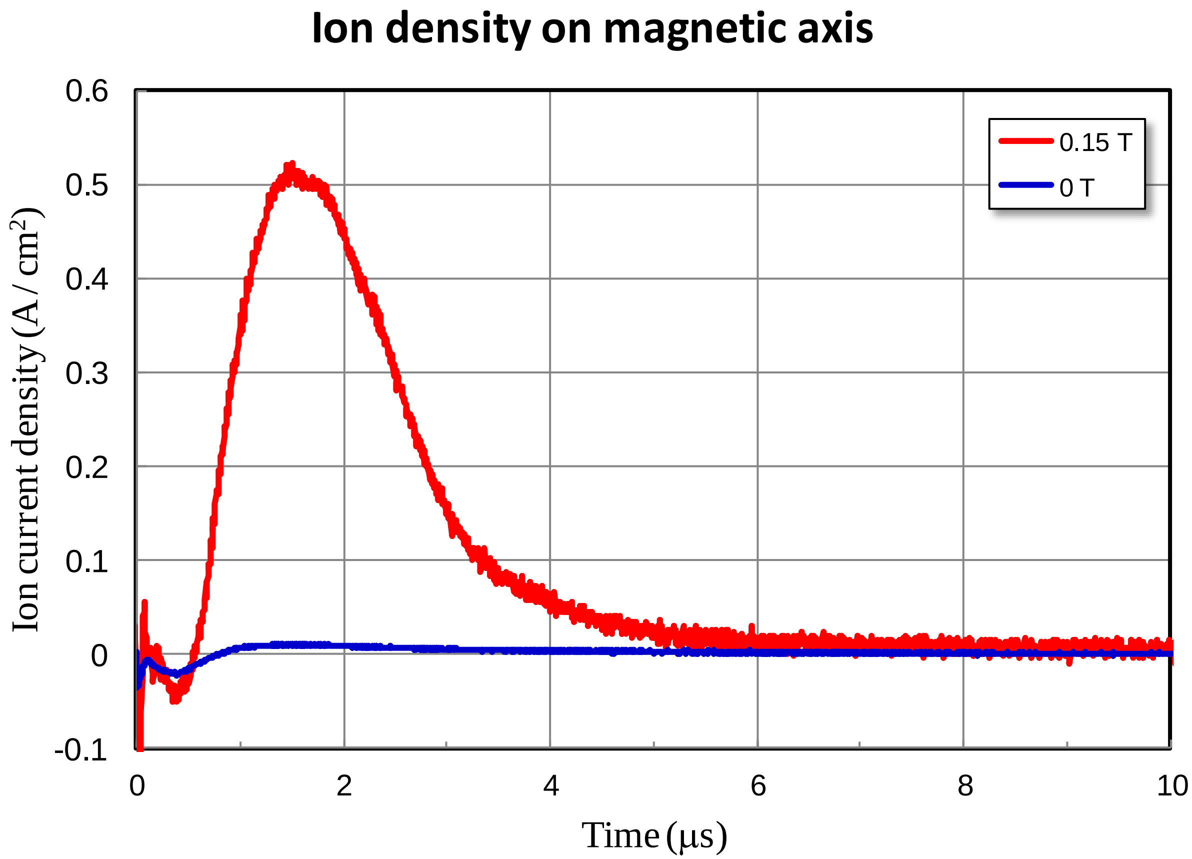
V (plasma edge speed) 10**6 cm/s

t (plasma expansion time to the next droplet) ; 0.1μS

Density is 10-6 times lower from initial droplet**

Measured ion flux at Faraday Cup

Ion beam duration < 2μS



Time parameters

Plasma exhaust 2μS

Droplet interval 7μS

(1mm interval, 150kHz)

Repetition rate increase to 150kHz is necessary for kW IF power realization

Component technologies improvement

- Droplet generator at 150kHz operation
  ;150m/s droplet final speed required
- Picosecond, ~mJ solid state laser as pre-pulse
  ; thin disc laser
- CO_2 laser dual mode operation at 150kHz
- Gas free vacuum environment
  ; laser resonant ionization of neutrals

Fast droplet flow by higher back pressure

§ Droplet Technology

Continuous Jet Method [Rayleigh' s Theory]

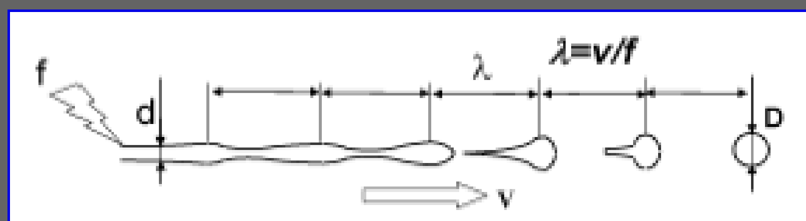
- Uniform droplets generation from continuous jet

Surface Position : r

$$r = (d/2) + \alpha e^{qt} \cos(2\pi x/\lambda)$$

$$q_{max} = 0.97\sqrt{(\sigma/\rho d^3)} \text{ @ } \lambda/d = 4.51$$

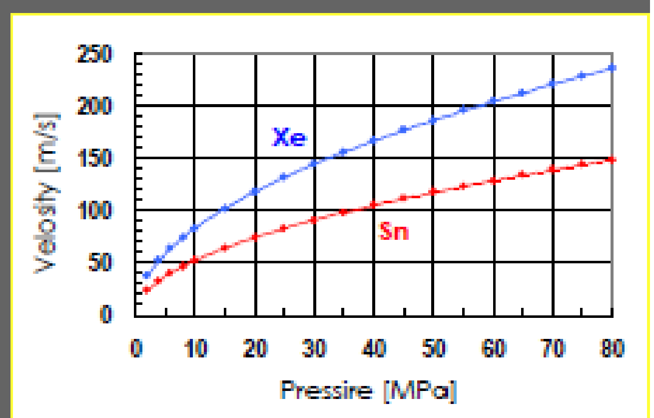
d : Jet dia.
σ : Surface Tension
α : Initial Disturbance
q : Growth rate
ρ : Density
f : Frequency



Bernoulli' s theorem

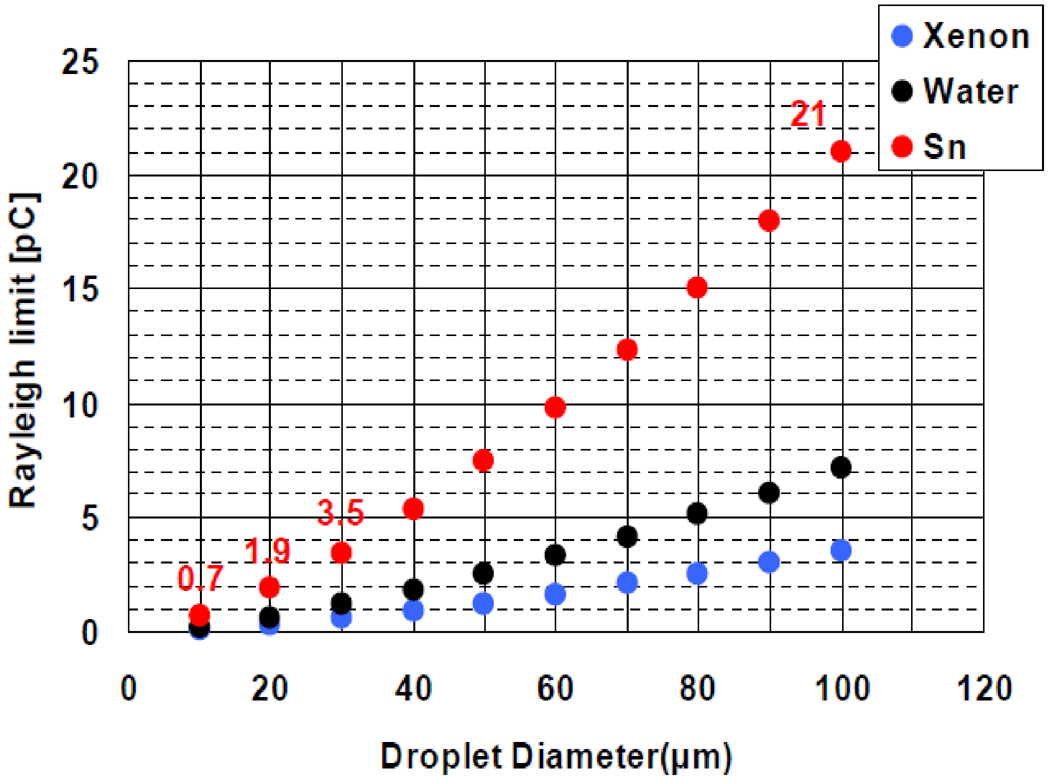
$$v = \sqrt{\frac{2\Delta P}{\rho}}$$

v : Velocity
p : Pressure
ρ : Density



Electrostatic acceleration

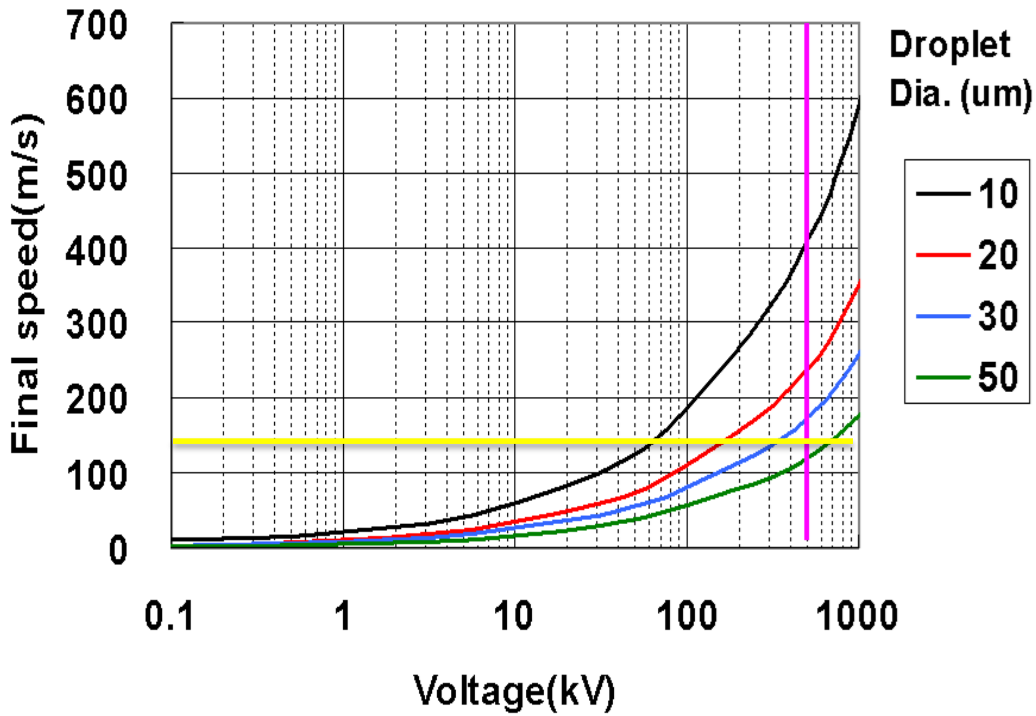
Rayleigh limit
(maximum charge on droplet)



$$Q\max = \sqrt{64\pi^2 \varepsilon_0 r^3 \sigma}$$

ε_o : permittivity
r : Droplet radius
σ : Surface tension

Droplet acceleration to 150m/s



$$v_{final} = \sqrt{\frac{2QV}{m} + v_0^{\,2}}$$

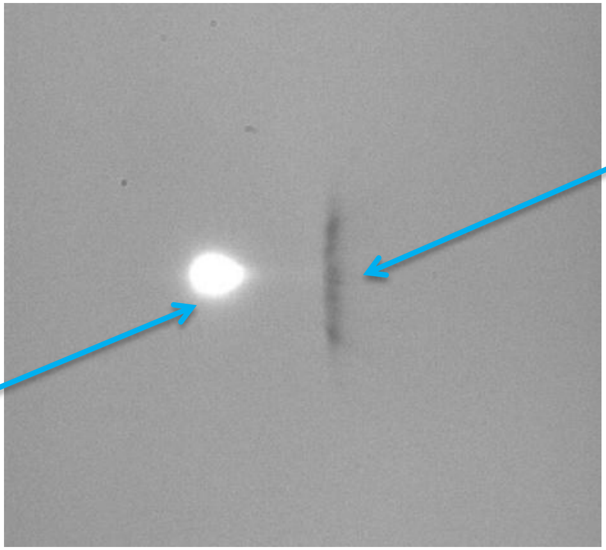
Q: Charge
V: Acceleration voltage
σ: Surface tension
m: Mass
v_0: Initial speed

possible With 80kV static acceleration

150m/s droplet speed

Static high voltage limit

Mist target generation by picosecond ablation of Sn droplet



Mist target

Pre-pulsed droplet

Pressure in transient phase
;atomic motion + intermolecular force

$$P = \rho k_B T + \frac{1}{3V}\left\langle \sum_{i=1}^{N}\sum_{j<i} \vec{F}_{ij}\cdot\vec{r}_{ij} \right\rangle$$

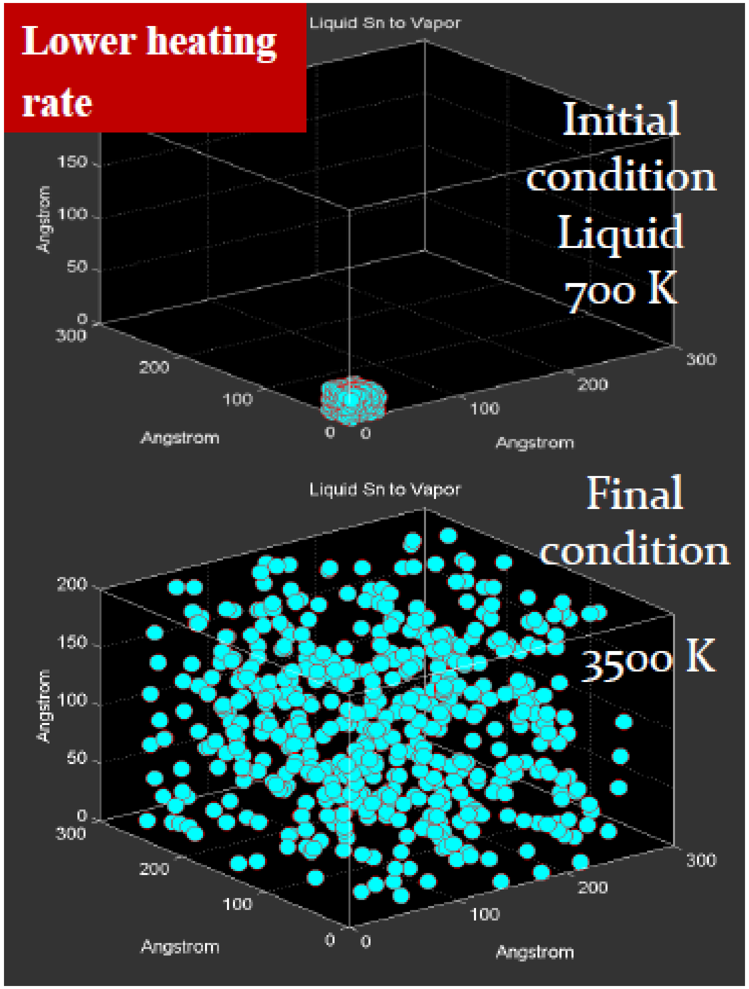
$$T = \frac{m}{3Nk_B}\sum_{i=1}^{N}\left(\sum_{\alpha=1}^{3}\left(v_{i,\alpha} - \bar{v}_{\alpha}\right)^2\right)$$

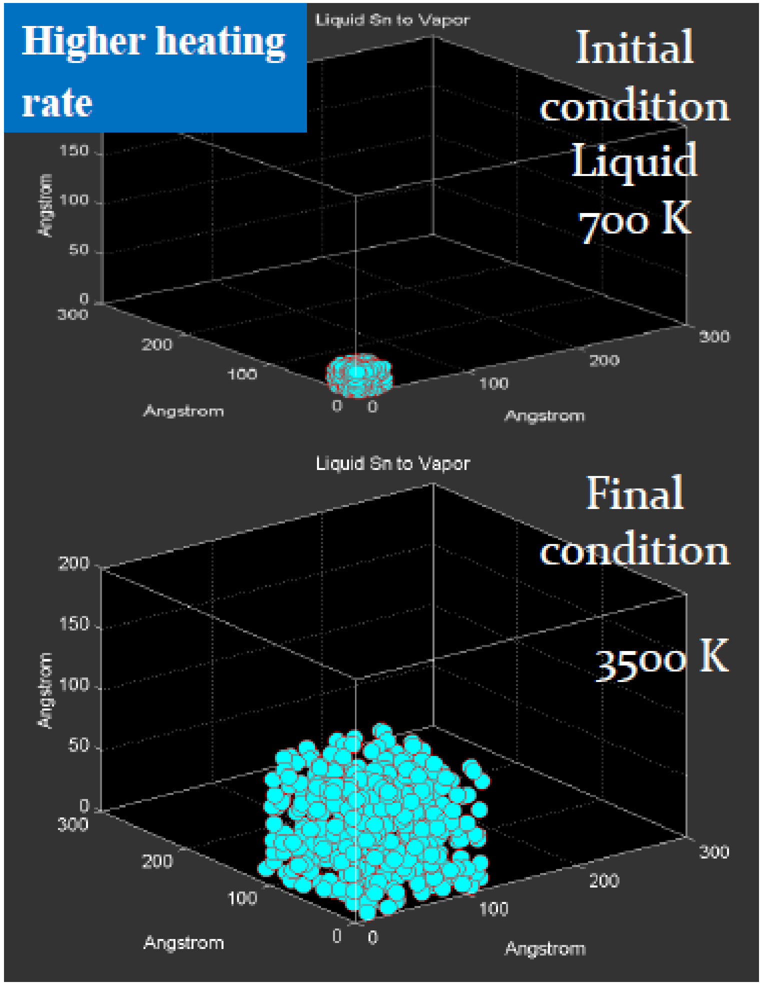
P(fast heating) > P(slow heating)

Molecular dynamics simulation

Boiling & Vaporization

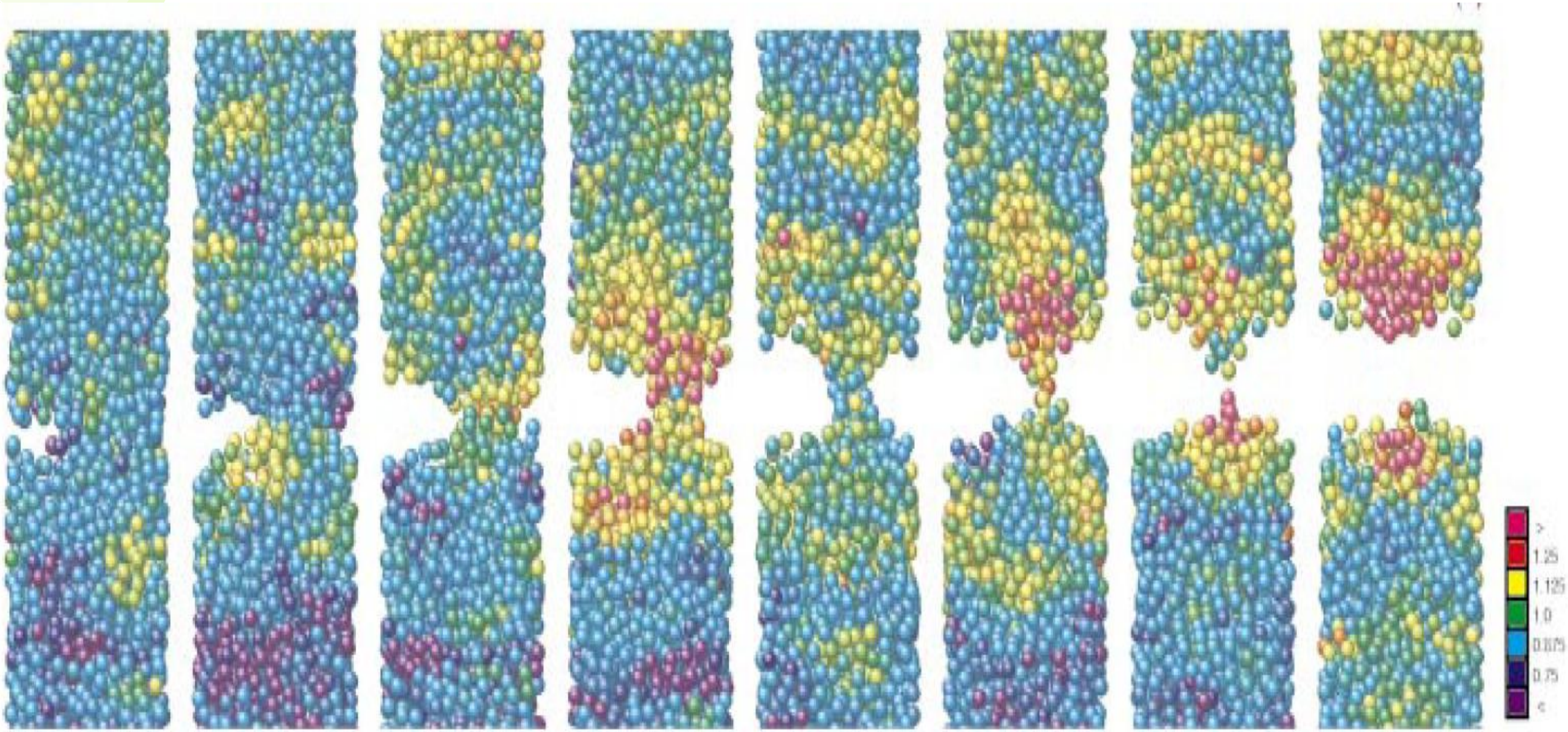
Inertial confinement effect





Thermal history changes the thermodynamic pathways.

Pressure dynamics from MD calculation

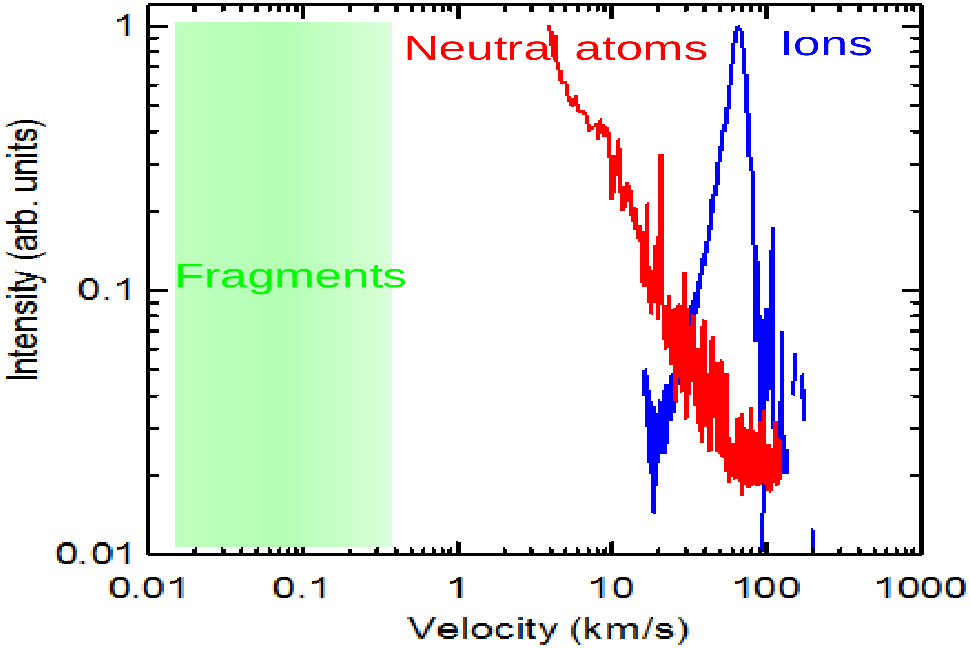


(a) 29.4ps (b) 30.4ps (c) 31.4ps (d) 32.4ps (e) 33.4ps (f) 34.4ps (g) 35.0ps (h) 35.8ps

Strong impulse continues less than 10ps due to plasma shield

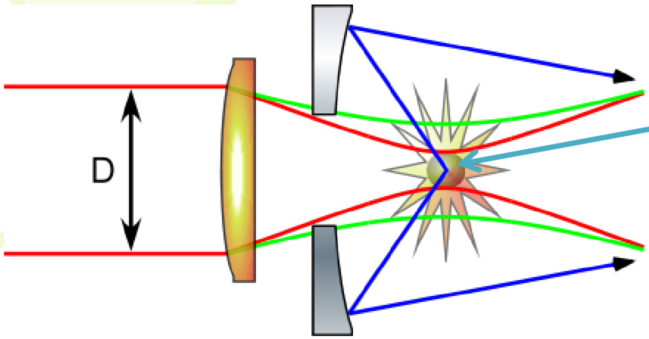
Measured Speed ; ions, neutrals and fragments

in pre-pulse;100μm diameter Sn droplet, 10ns laser

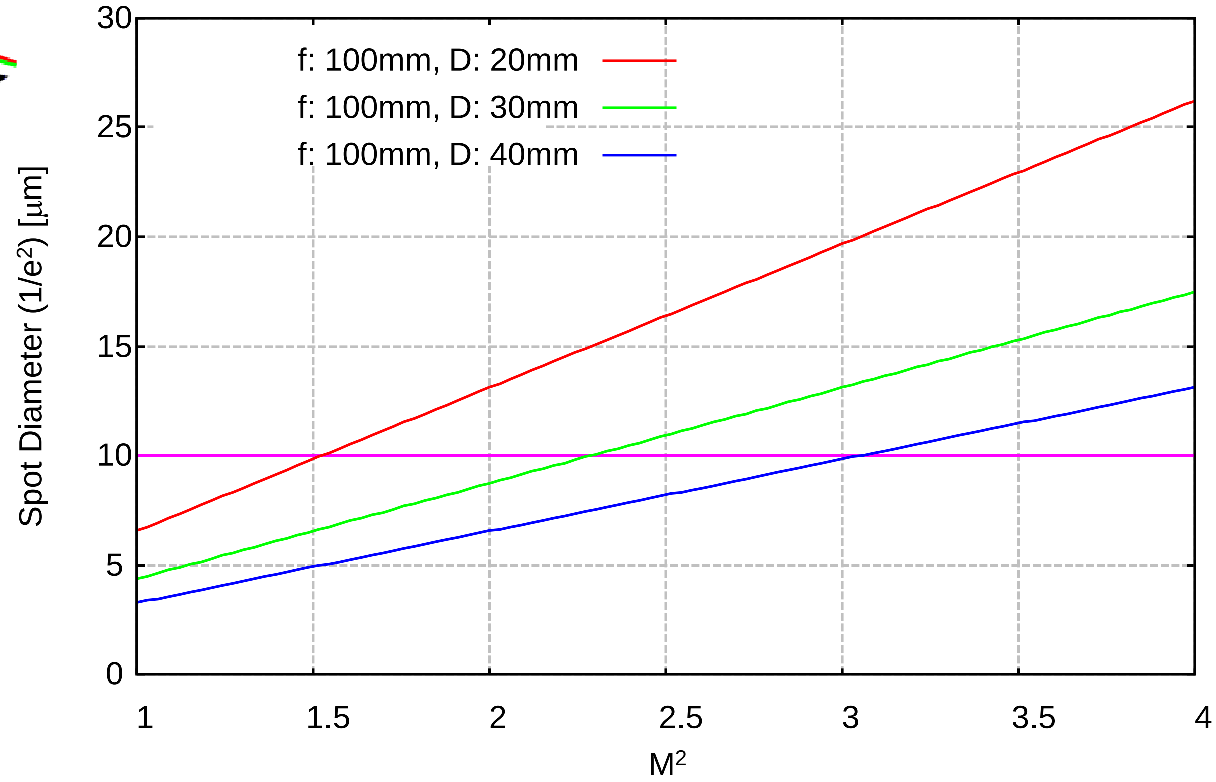


Pre-pulse laser is effective in ps pulse width as impulse for droplet spallation

Focusing Property of Pre-pulse Laser



Target size: $\phi 10\mu m$

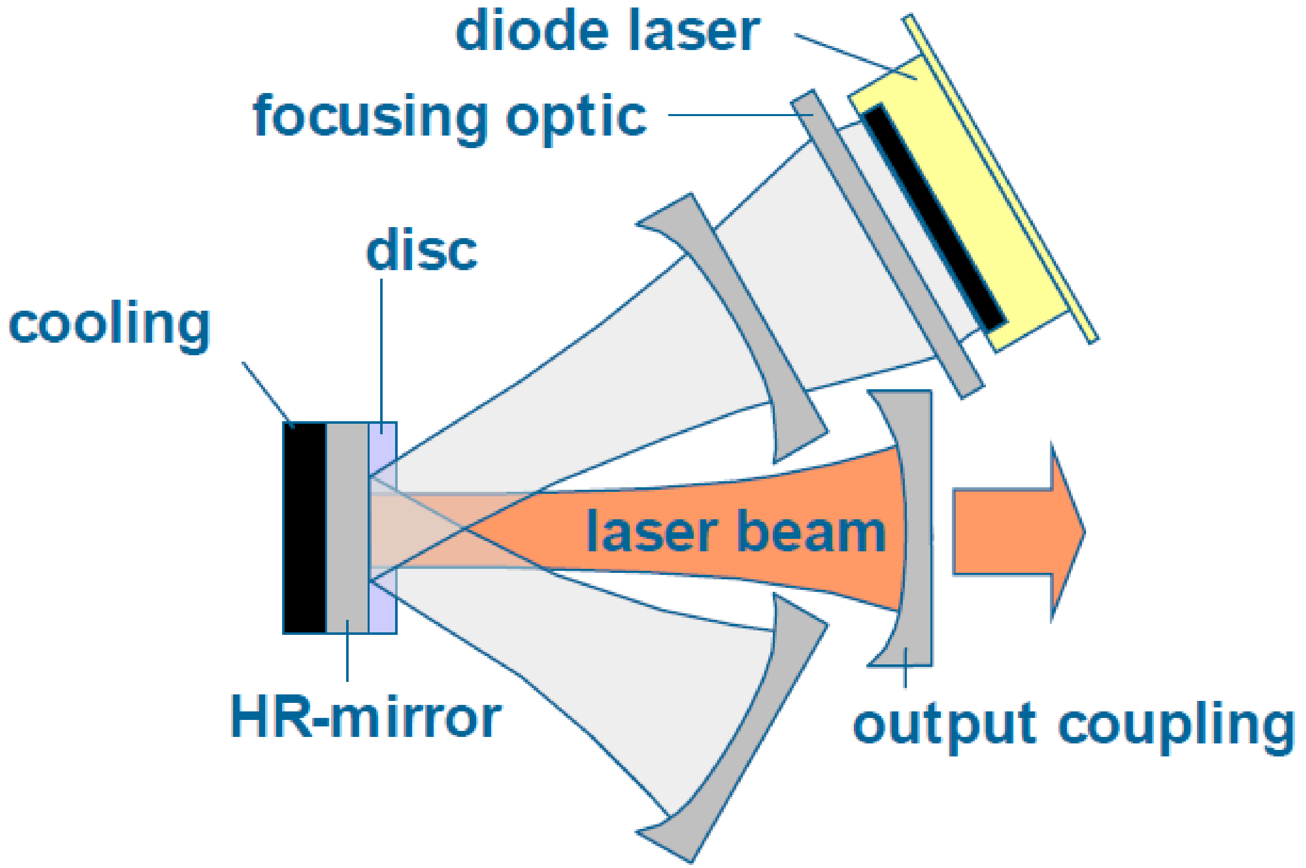


Target size: 10μm

Focal length of lens: f=100mm

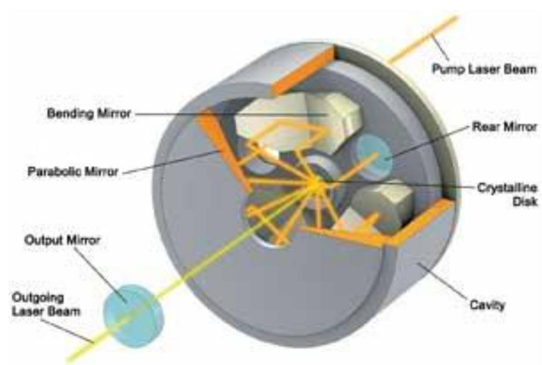
- D=20mm
  - $M^2<1.5$
- D=30mm
  - $M^2<2.3$
- D=40mm
  - $M^2<3$

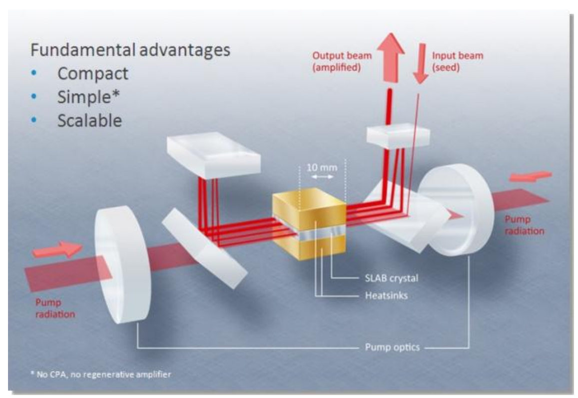
Thin disc laser configuration



High Energy Picosecond Pulse Sources

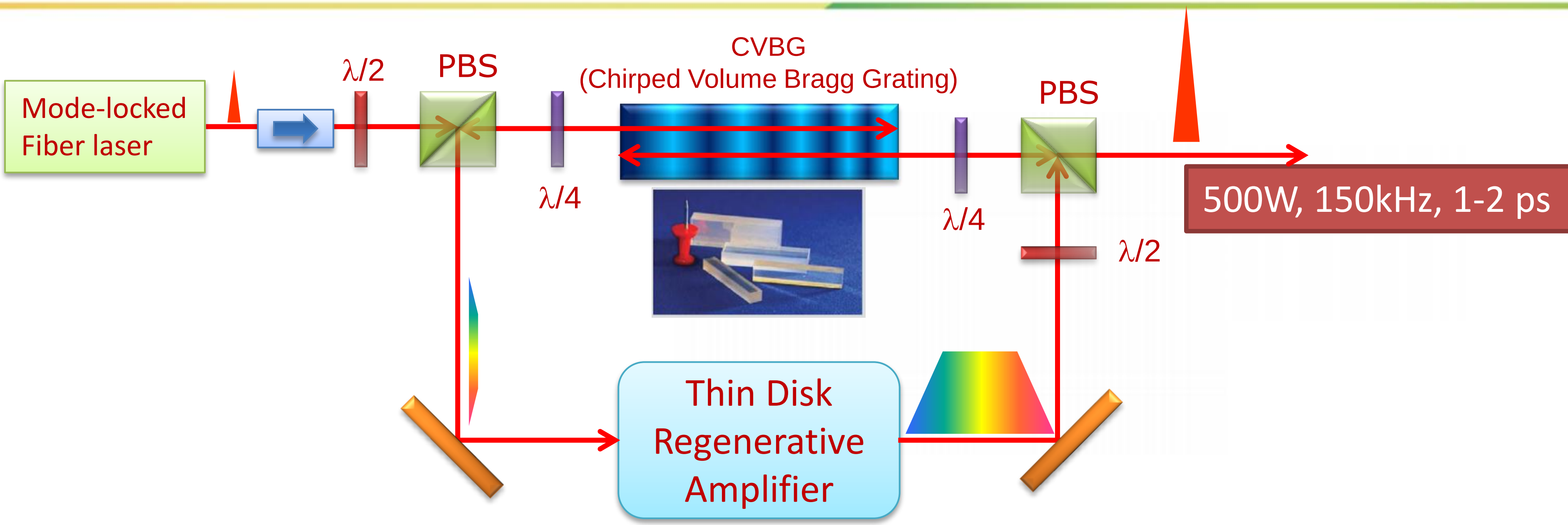
	Dual Thin disk Regen. (MPQ, 2012)	Single Thin disk Regen.[1] (MPQ, 2009)	Single Thin disk Regen.[2] (MBI, 2011)	Single Thin disk Multi-pass[3] (MBI, 2012)	Single Thin disk Multi-pass[4] (DESY, 2012)	Innoslab[5] (DESY, 2011)	Innoslab[5] (DESY, 2011)
Repetition rate [Hz]	1,000,000	3,000	150	100	10 (100kHz burst)	12,500	100,000
Pulse energy [mJ]	0.23	25	305	548	3560 (80 pulses)	20	2
Average output [W]	230	75	45.8	54.8	35.6	250	200
Pump energy [J]	CW	0.1	3.8	6.0	16.1	CW	CW
Pump power [W]	600	280	562.5	600	161.2	600	600
O-O Efficiency [%]	38.3%	26.8%	8.1%	9.1%	22.1%	41.7%	33.3%

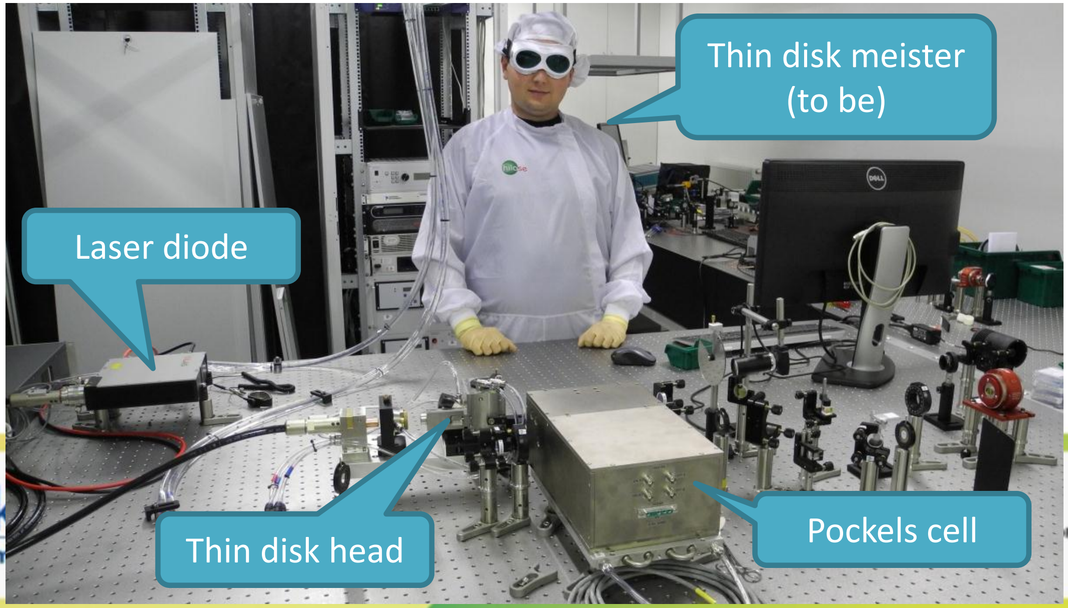




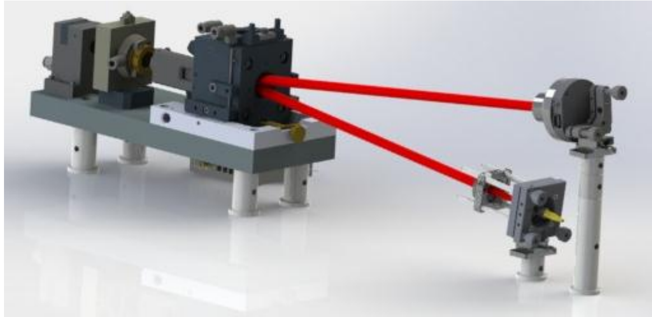
[1] T. Metzger *et. al.*, Opt. Lett. **34**, pp. 2123 (2009).
[2] H. Stiel *et. al.*, PTB Seminar EUV Metrology (2011).
[3] R. Jung *et. al.*, Disklaser Workshop (2012).
[4] M. Schulz *et. al.*, Opt. Express **20**, pp. 5038 (2012).
[5] M. Schulz *et. al.*, Opt. Lett. **36**, pp. 2456 (2011).

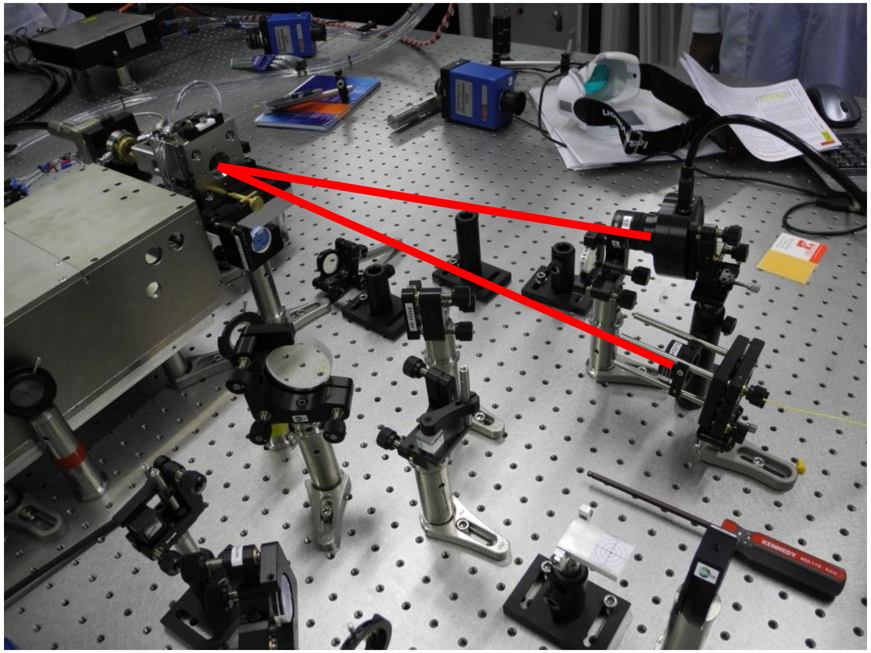
Table-top High Power Laser Source in HiLASE



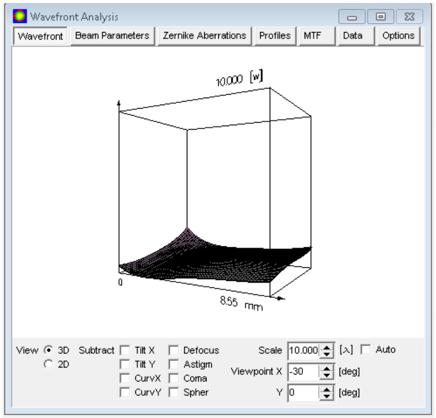


In-situ Measurement of Thin Disk Deformation

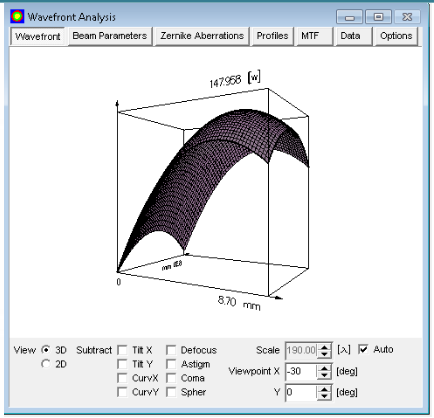




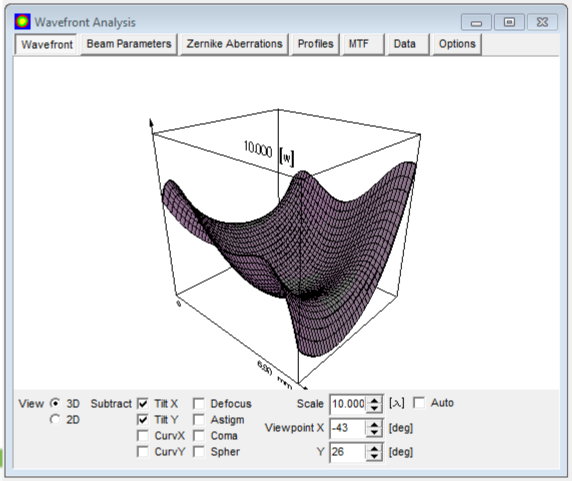
Wavefront from flat mirror



Wavefront from concave mirror (R=400mm)



Wavefront from thin disk



Fyzikální ústav
Akademie věd ČR, v. v. i.

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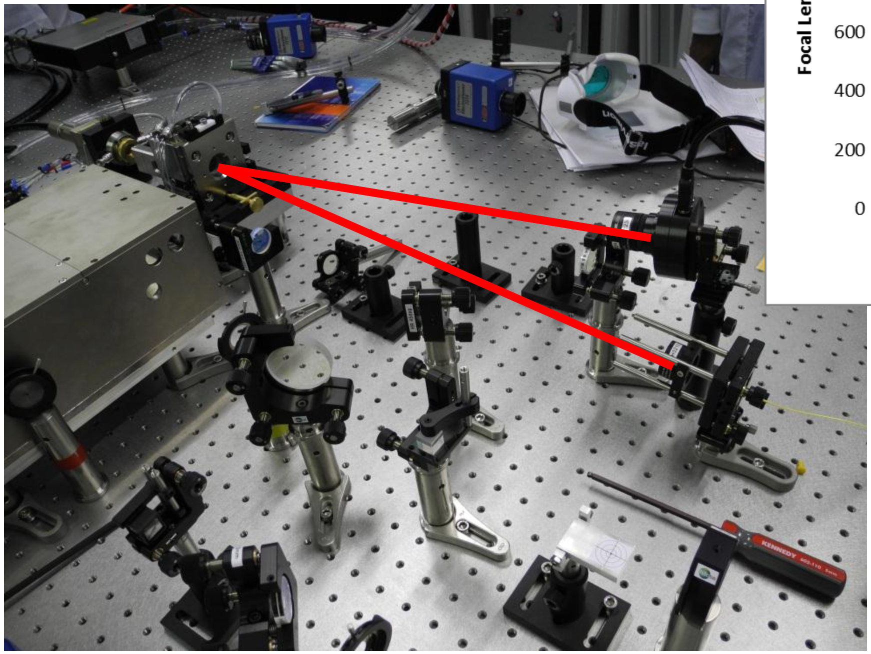
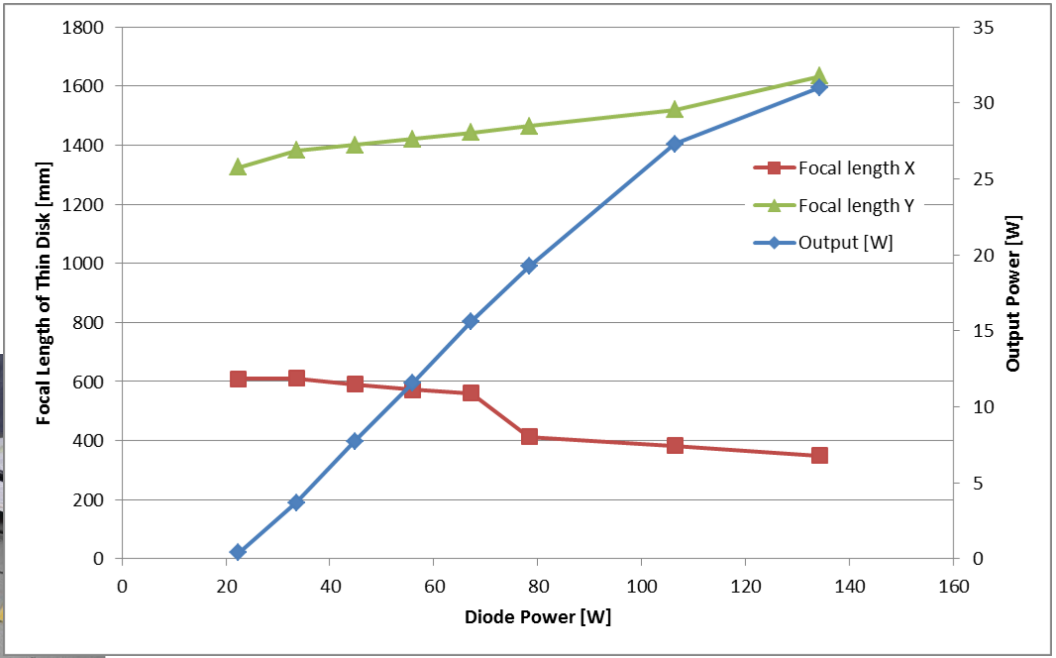
Preliminary Result of Thin Disk Deformation Measurement





RP1 Group

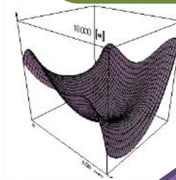
P. Severova

Analysis by simulations
Exploring improvements

Comparison with numerical model

T. Miura

Evaluation of thin disk deformation ,gain (ASE) etc.



Suggestions for improvement

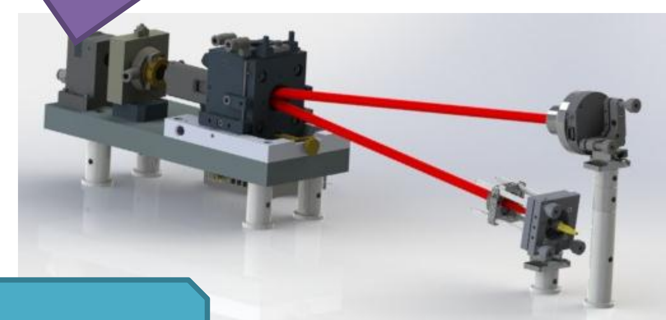
Real-time measurement

M. Chyla

M. Smrz

O. Novak

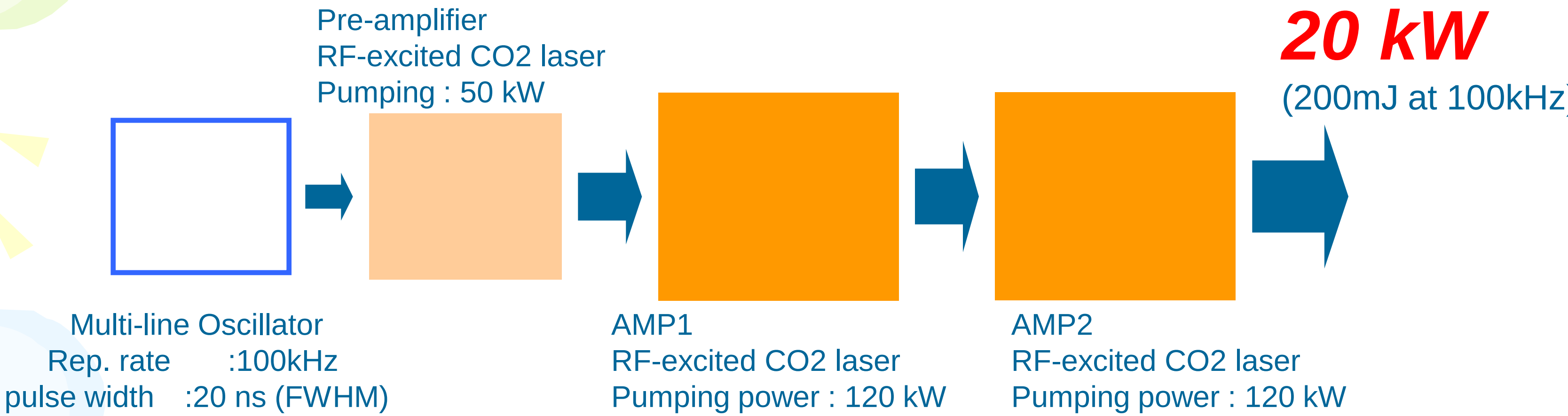
High energy Thin disk
Regenerative amplifier
Ring amplifier



A. Endo
(RP1 leader)

Applications (EUV BEUV HHG …)

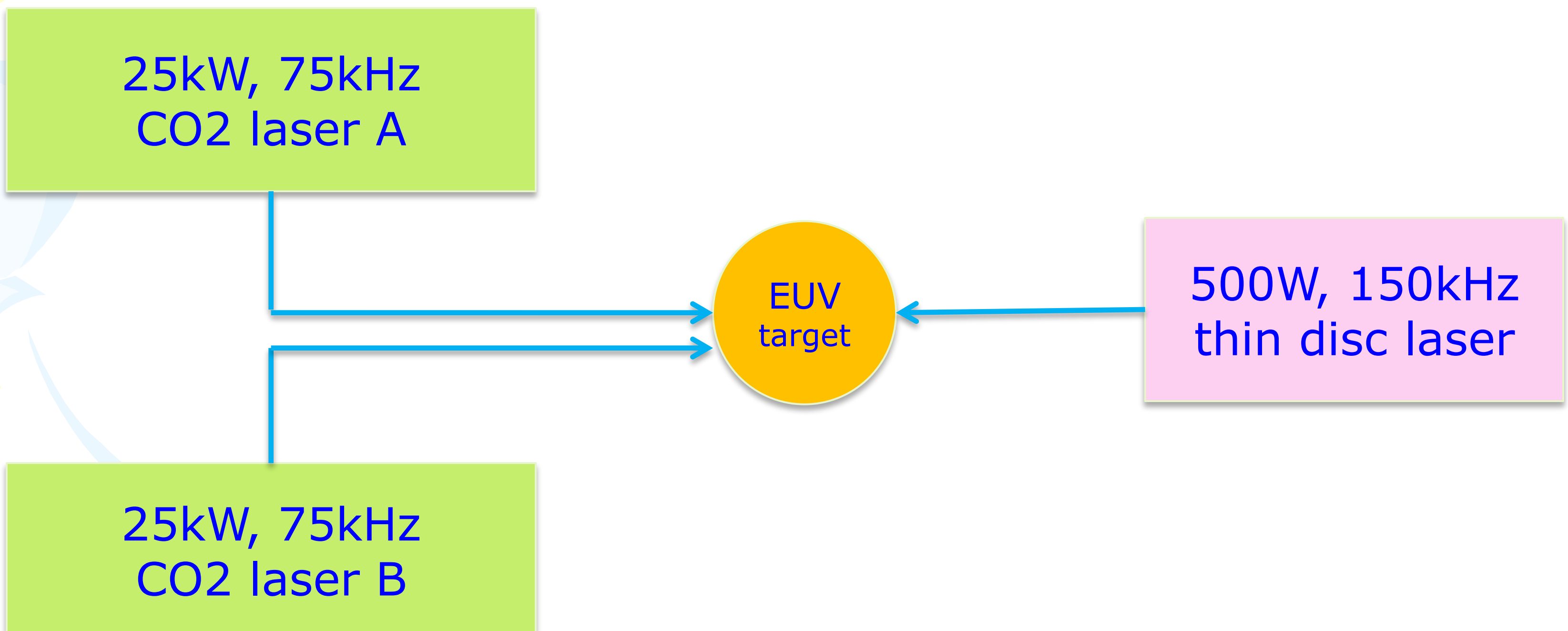
Multi 10 kW Short Pulse CO_2 laser MOPA system



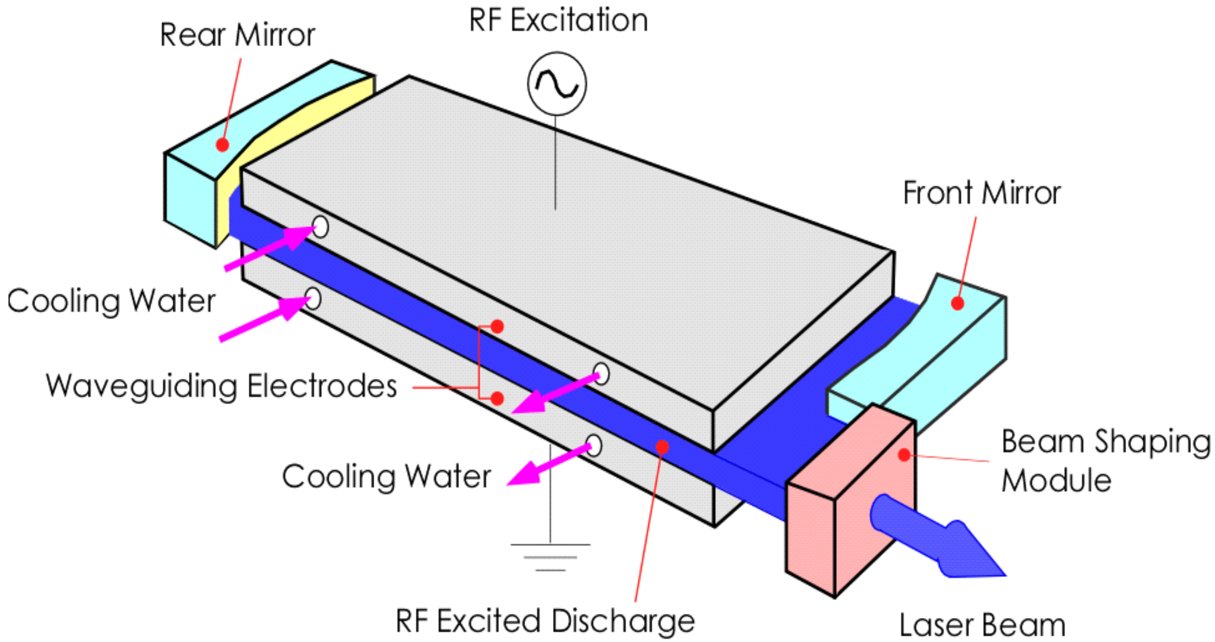
One beam, 25 kW is a reasonable estimate

- Power Limitation
  - ***Wavefront distortion***
    - ⇒ Thermal distortion of windows
  - ***Filling Factor***
    - ⇒ Laser beam diffraction ; beam delivery design
  - ***Stage isolation***
    - ⇒ Loss due to amplified spontaneous emission

Configuration of 150kHz, 1kW EUV source



Diffusion-cooled slab CO_2 laser as a pre-amplifier

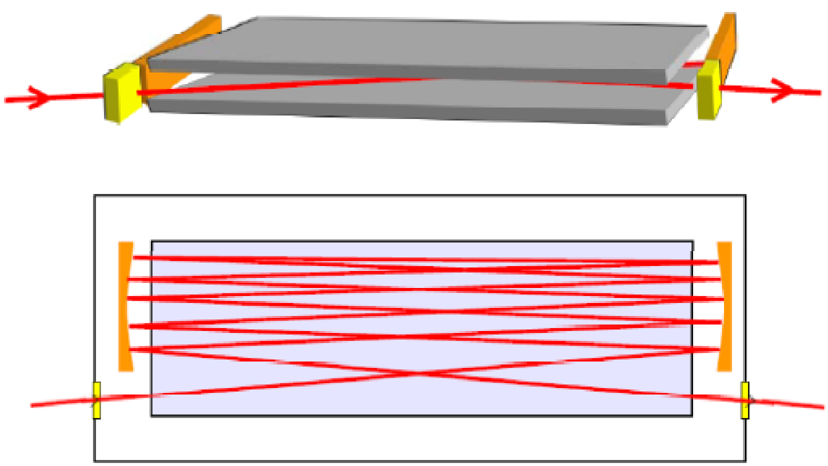


- high efficiency energy extraction
- high beam quality
- excellent thermal stability
- no gas flow
- compactness
- low noise
- not expensive maintenance

Multi-pass amplifier arrangement

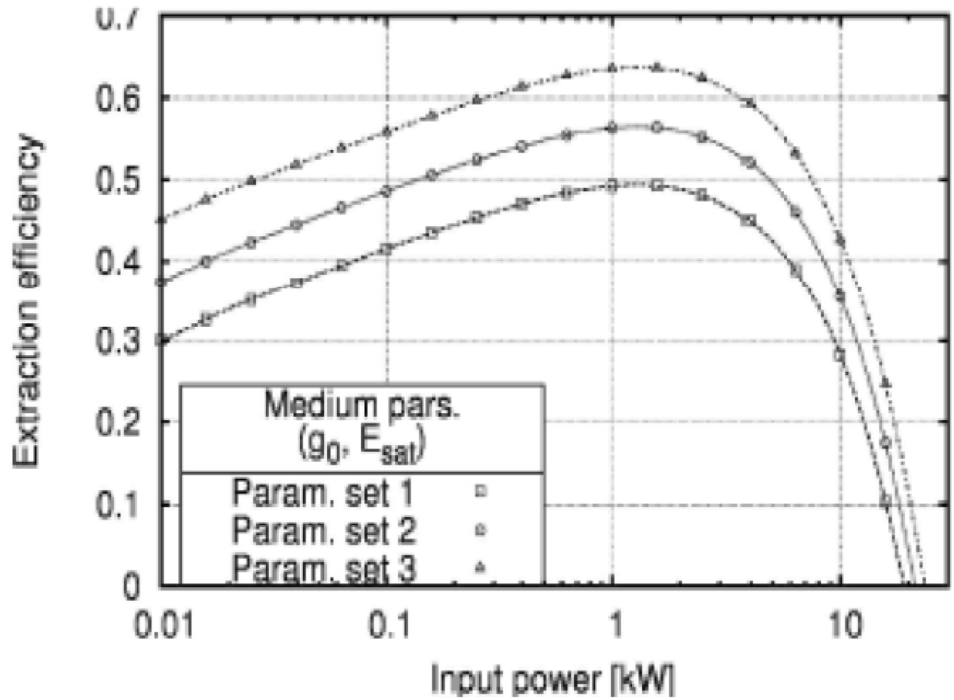
➢ Multi-pass amplifier

Slab-waveguide amplifier based on RF-discharge excited diffusion-cooled CO_2 lasers



➢ Extraction efficiency

Calculated performance of multi-pass pre-amplifier



Maximum extraction efficiency* : 35-60%
Input for max Extraction Efficiency : 1-3kW

*As compared to CW power output at full RF duty

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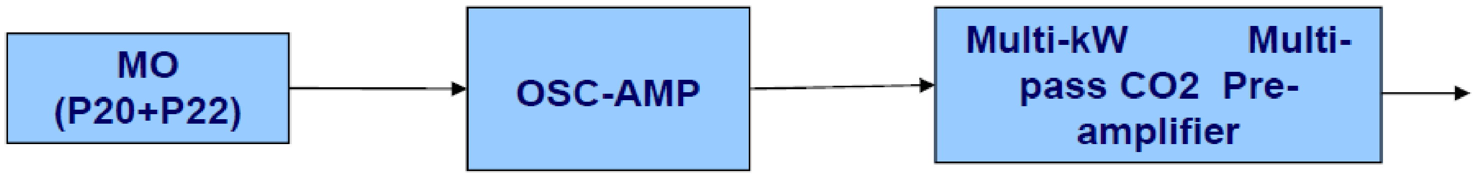
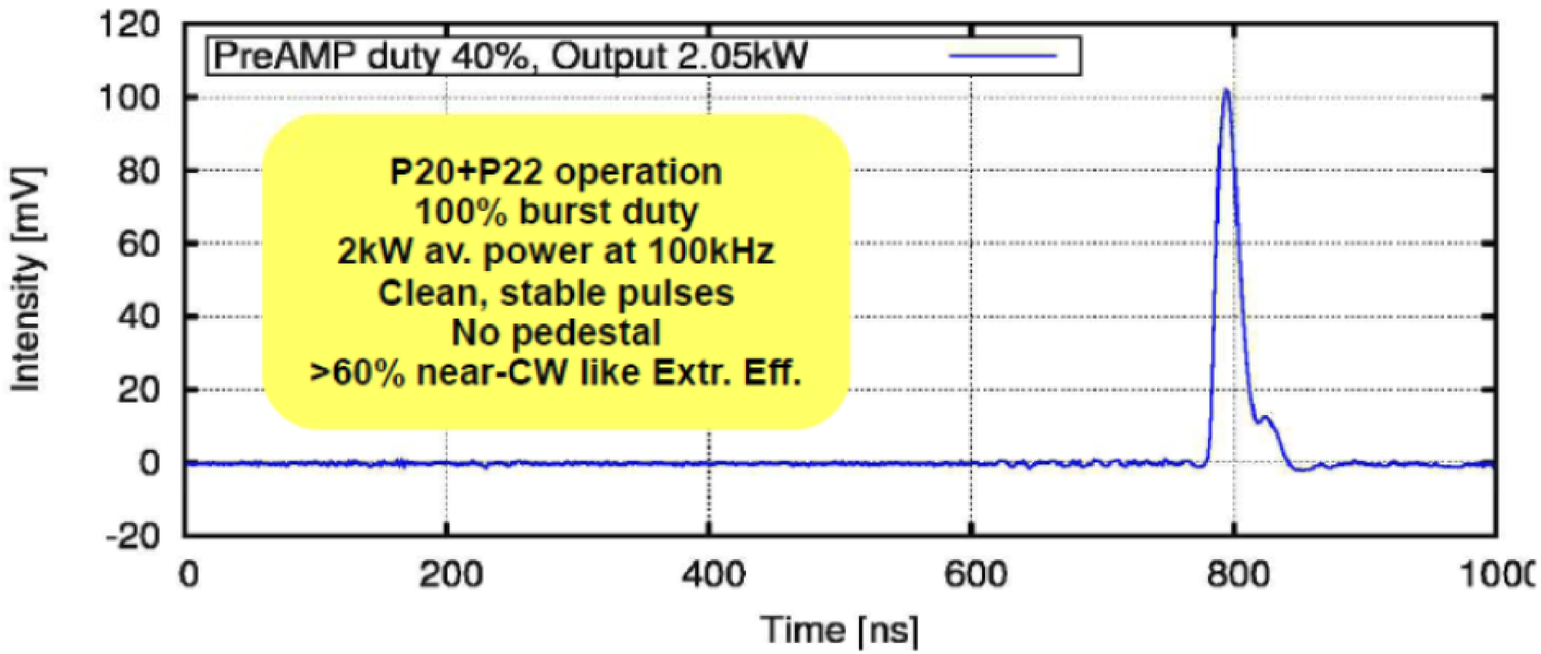
Multi-line amplification results : Pre-AMP





2kW output was achieved at near-CW extraction.

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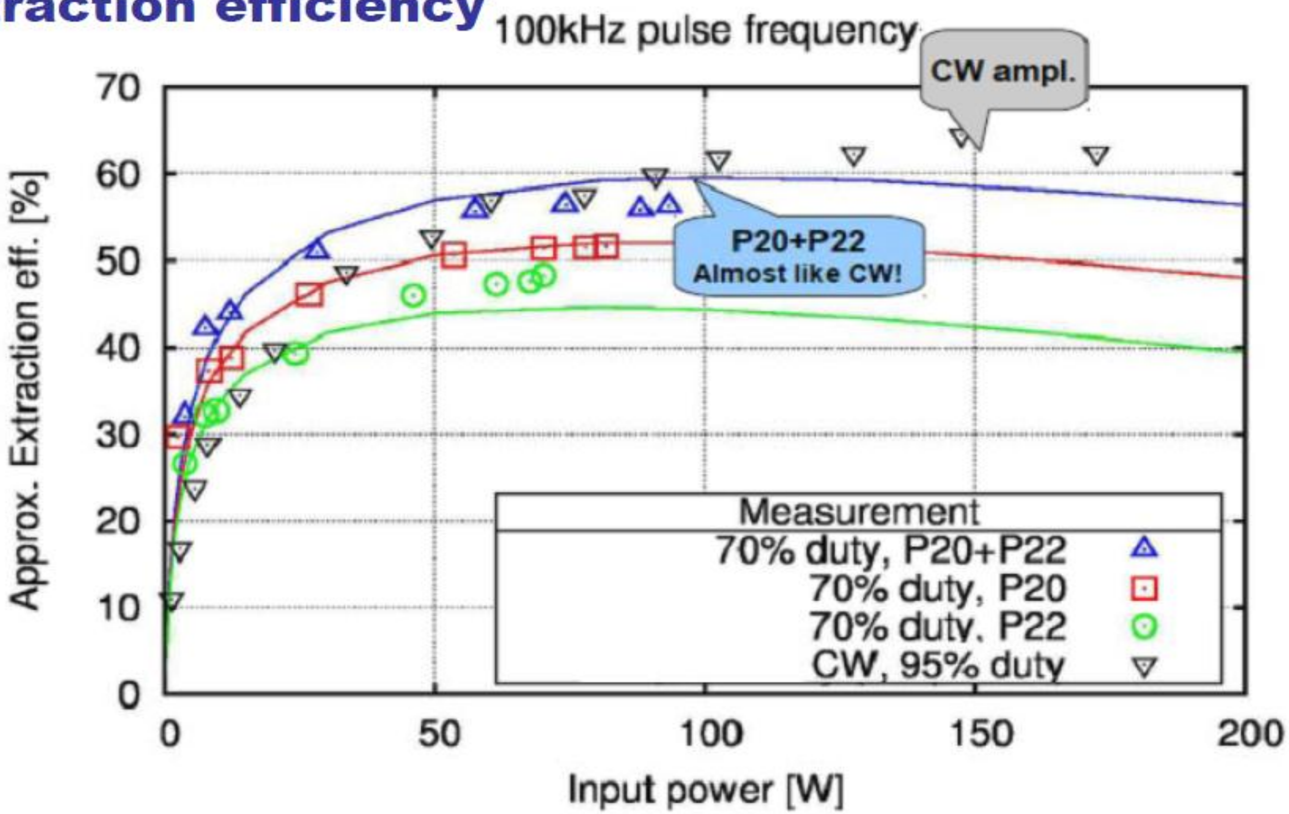
Multi-line amplification results : OSC-AMP

- **Extraction efficiency**



10% energy extraction improvement using 2 lines (P20+P22) as compared to single line (P20) was confirmed

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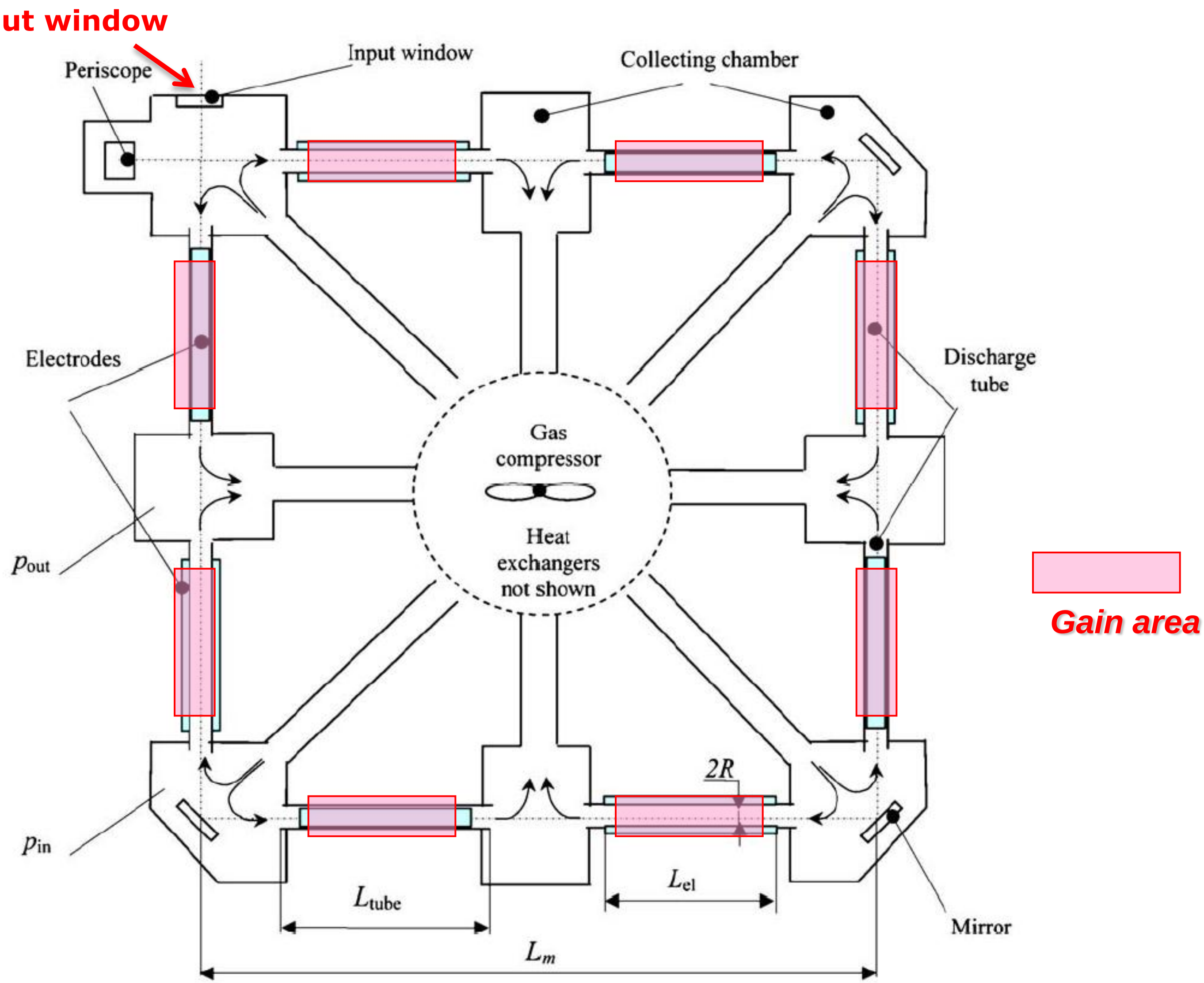
Discharge tubes of main axial flow amplifiers

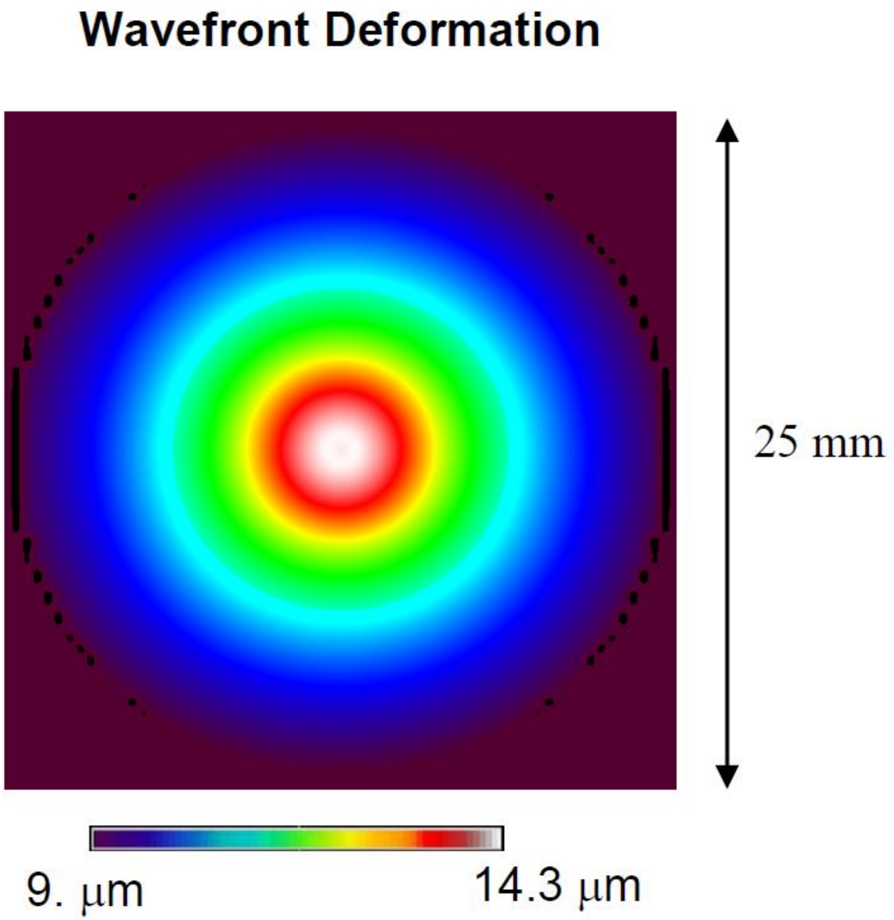


Two stage structure

OPD(optical path difference)

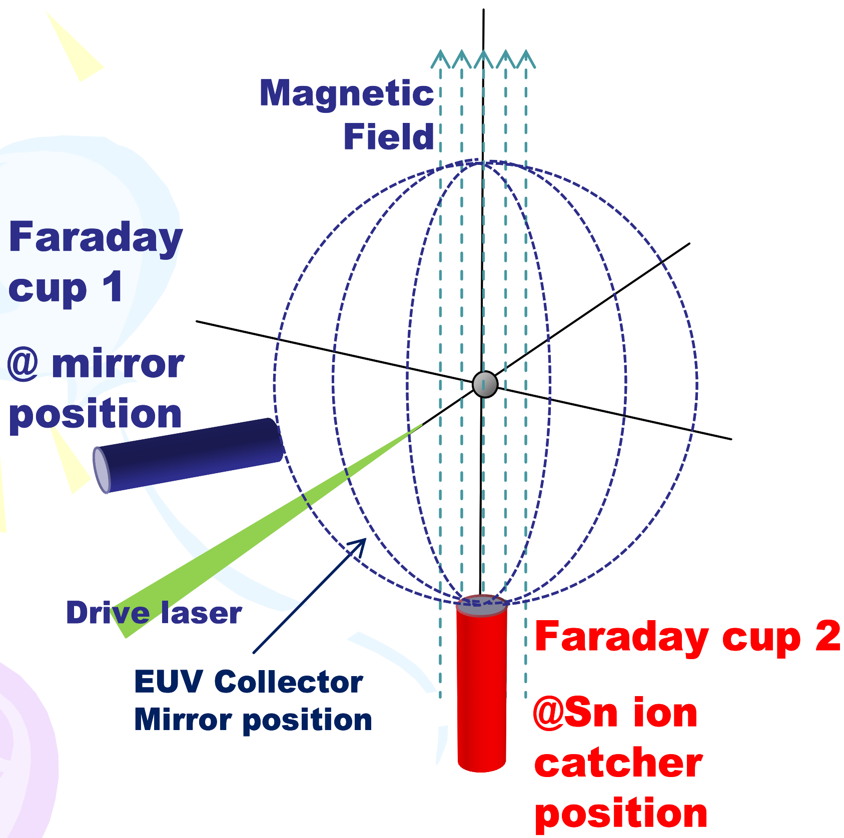
50kW/cm2 with d=7mm

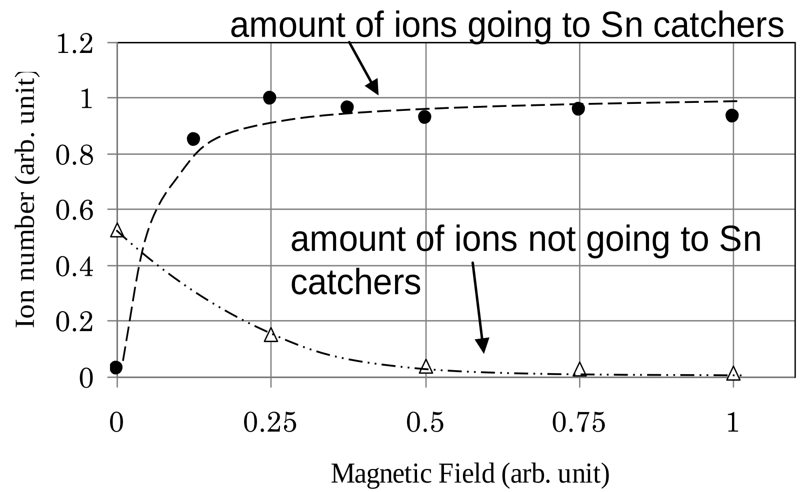
ZnSe (12.5mm thick)

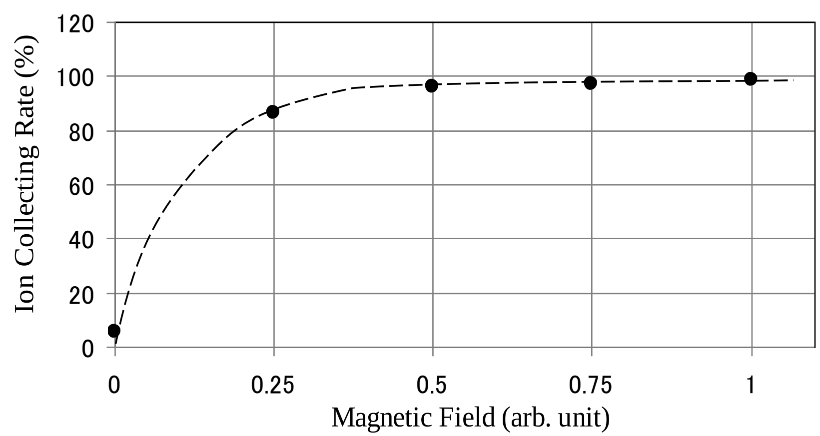


Sn vapor control for better EUV collection efficiency

Ion and neutral particle drift in transport magnetic field

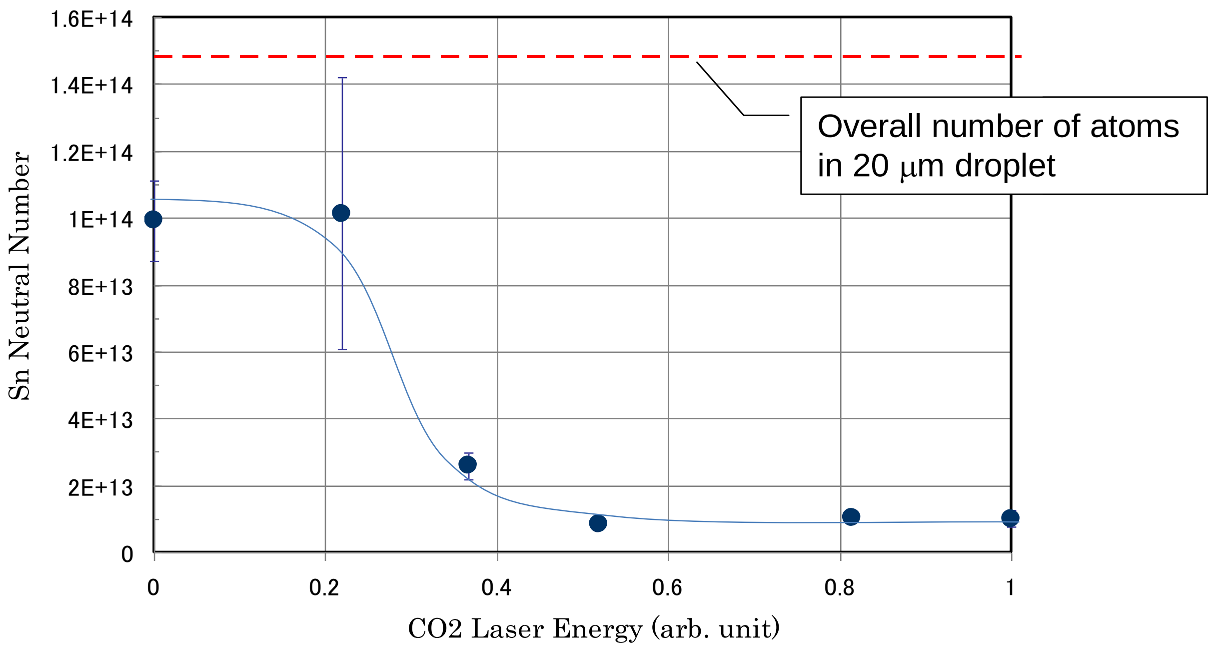




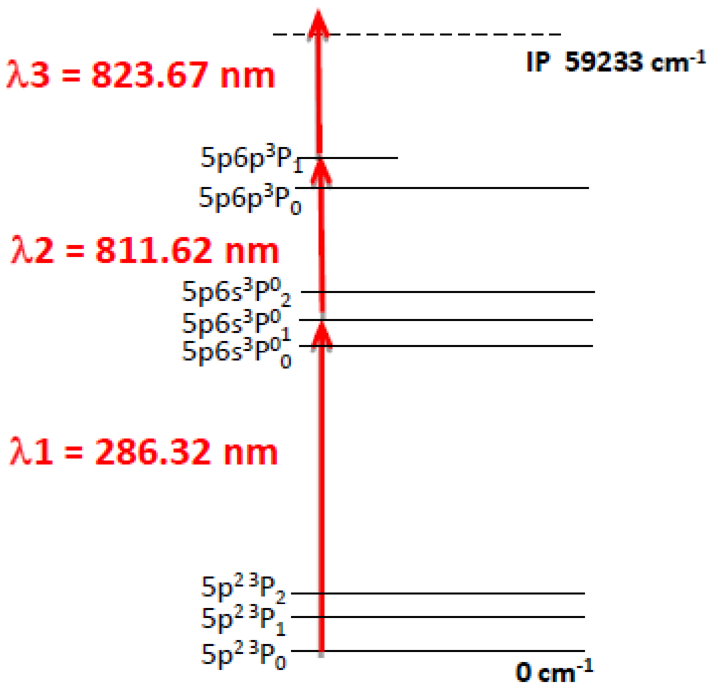


Remaining neutrals

>99% injected Sn atoms are collected by magnetic method.
Additional ionization increases further recovery,
and better EUV collection efficiency results.



Laser resonant ionization of Sn



Es=0.19mJ/cm2

Es=0.07mJ/cm2

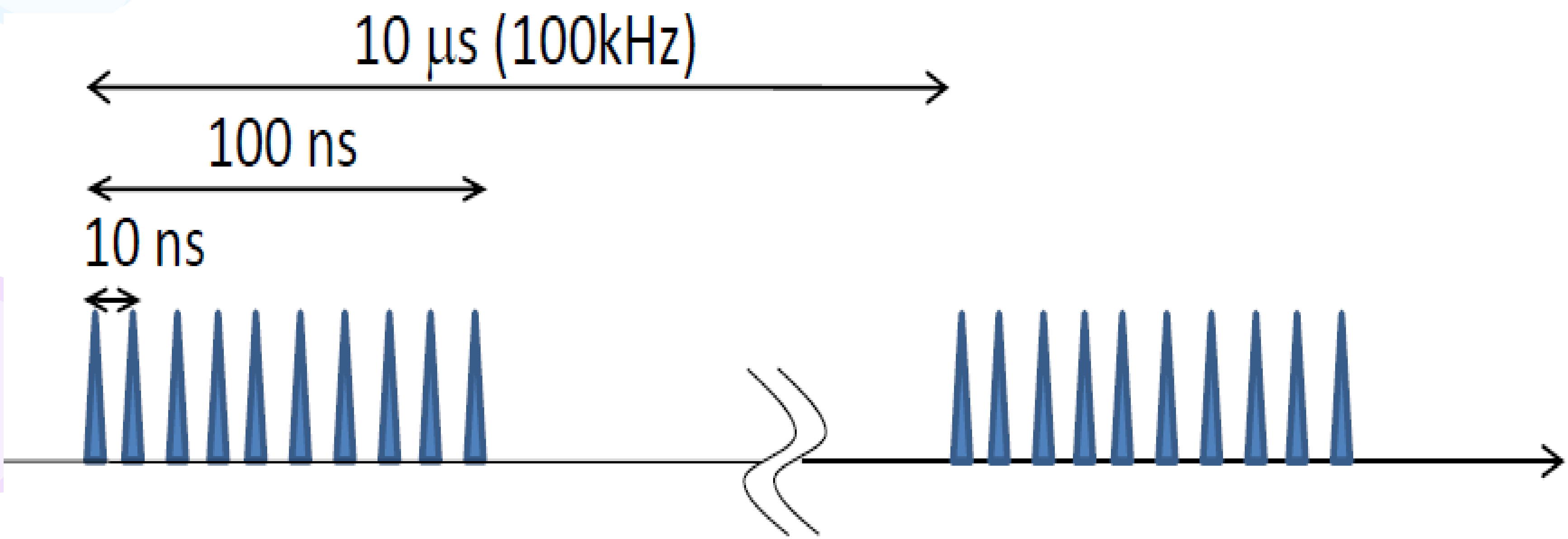
Es=1.38mJ/cm2

Energy diagram

Saturation fluence

Laser resonant ionization of Sn neutral atoms in partially ionized, cross correlated plasma (complex plasma)

$$Sn \rightarrow Sn^{+} + e^{-}$$



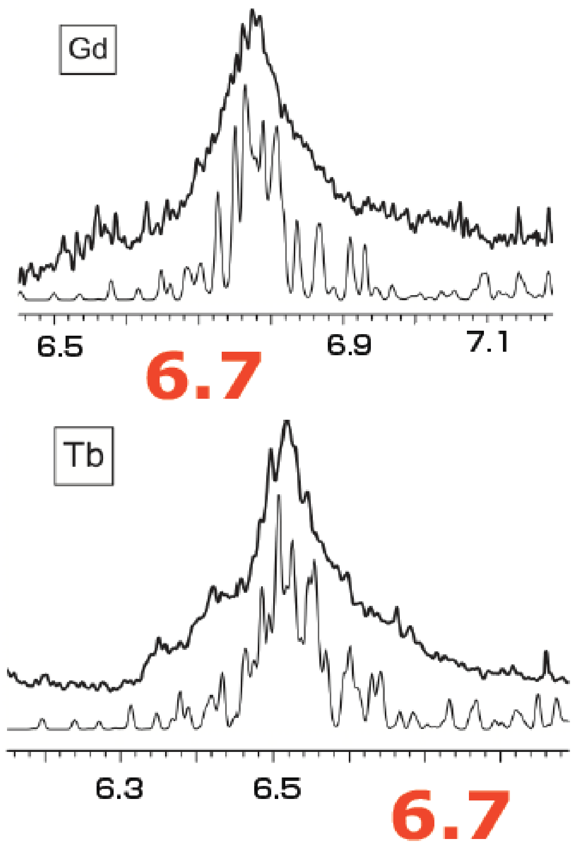
Intermediate Conclusion

LPP HVM architecture is scalable over 1kW

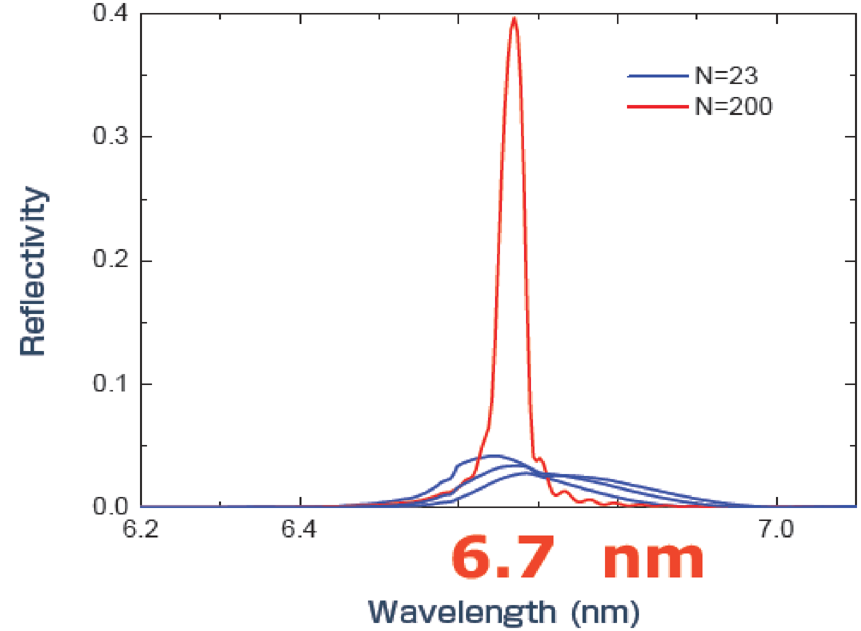
- Speedup of 10μm diameter Tin droplet to 150m/s
- Dual CO_2 laser modules are operated for 150kHz
- Sn Cluster formation by picosecond solid state laser
- Laser resonant ionization of neutrals

Scaling of HVM source technology to BEUV wavelength operation

6.7 nm: Gd, Tb plasmas



Mo/B_4C mirror



Fraunhofer
IOF

S. S. Churilov *et al*., Phys. Scr. **80**, 045303 (2009).

Effective conversion efficiency

Drive laser	Solid state laser	CO2 laser
Sn (/2%b.w.)	1.5%	4.5%
Gd (/0.6%b.w.)	0.5%	1.5%*

* Estimation from recent experiments (S11, T.Higashiguchi ; Plasma-based UTA emission in BEUV & water window spectral regions)

Operational parameters BEUV kW HVM source (1)

EUV IF power	**1kW (6.xnm)**
CO_2 laser power	160kW
Conversion efficiency	1.5%/0/6%b.w. *
Collection efficiency	40%
Mirror reflectivity	70% **

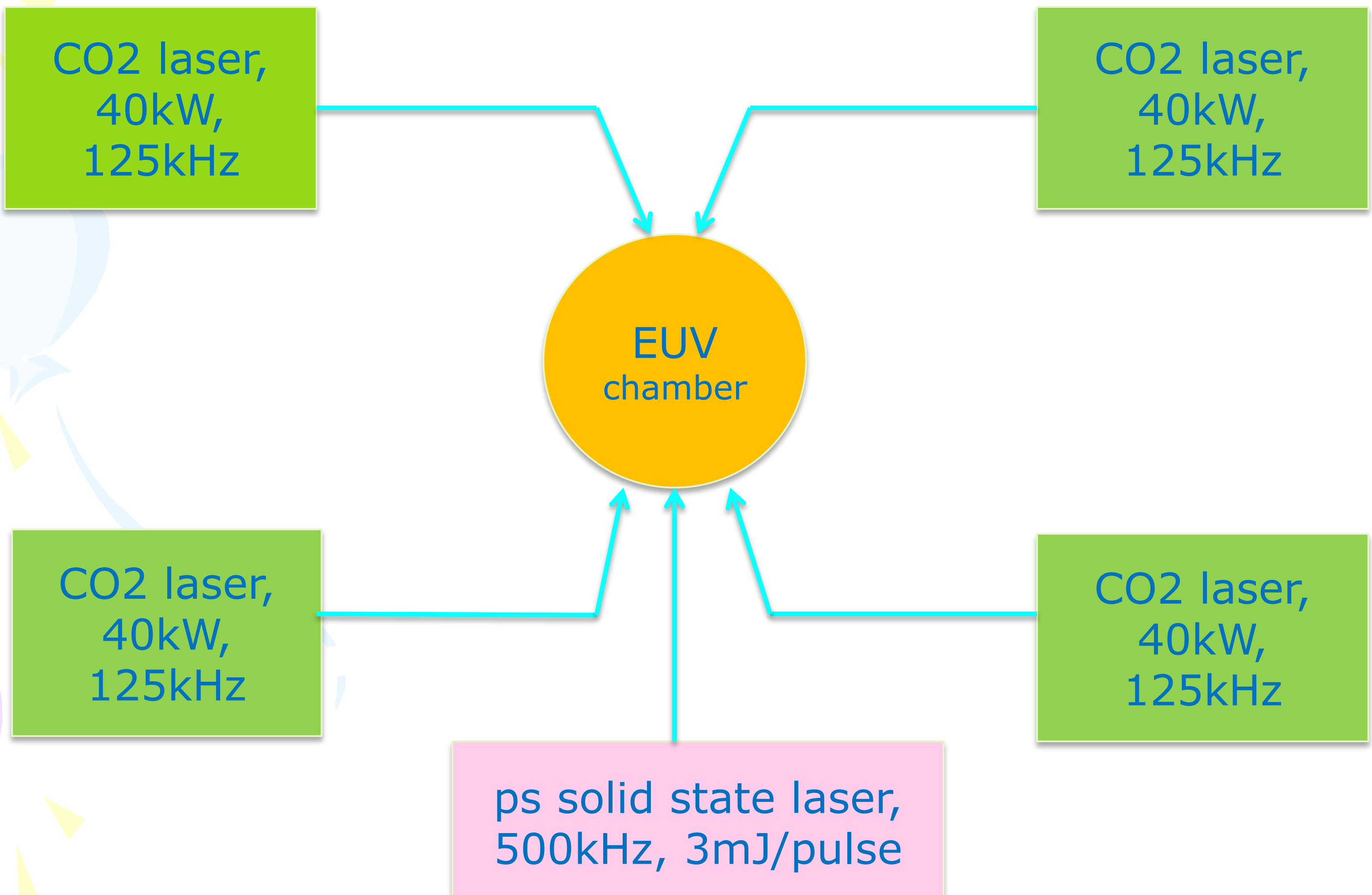
* very probable
** expected in this decade

Operational parameters BEUV kW HVM source(2)

Repetition rate	500kHz	Subjects
droplet	10μm Gd liquid	Molten temperature * 1312◦C
irradiation	double pulse	assume same spallation as Sn *
droplet interval	1mm	assume same expansion as Sn*
droplet speed	500m/s	< MV static acceleration
fuel recovery and reuse	full ionization and magnetic guide	Rare earth efficient laser ionization

* Gd droplet generator development desirable

Configuration of 500kHz, 1kW BEUV source



Coclusion

LPP HVM architecture is scalable over 1kW

BEUV HVM source needs x 3 drive laser power due to narrower bandwidth of C1 mirror

Comparison with non plasma approach meaningful